

OCEANS

THE INCREDIBLE SECRETS OF OUR BLUE PLANET



Meet the detectives who are
using DNA to track sharks

Gotta scan 'em all!
The project to image
every fish on the planet

Rethinking fish intelligence

How we can clear the
oceans of plastic

What if we banned fishing?

Protecting the deep sea
from bounty hunters

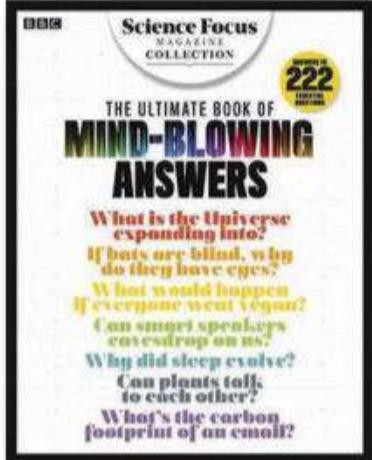
Groundbreaking tech that's
exploring the ocean's depths

The weird animals that
live hundreds of metres
below the waves

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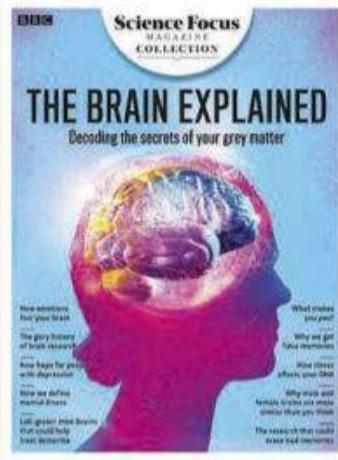
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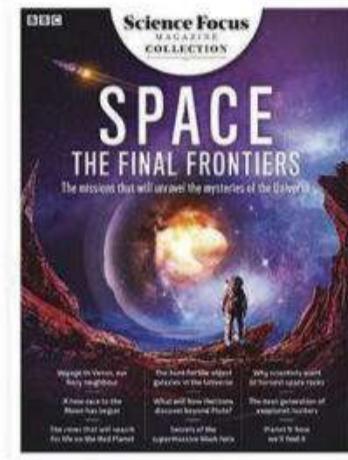
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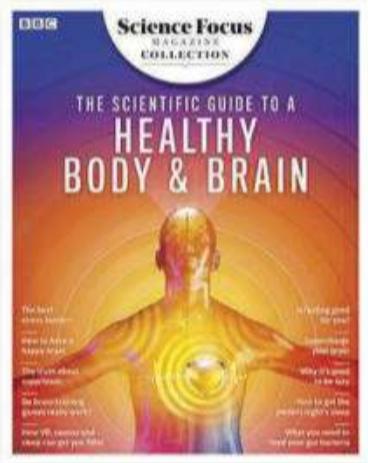
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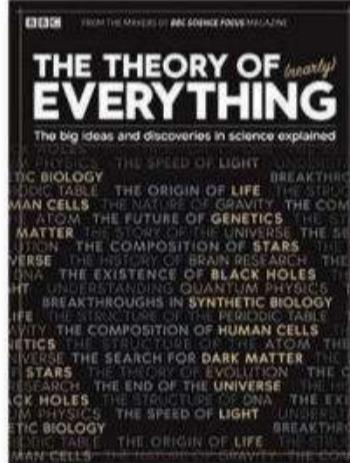
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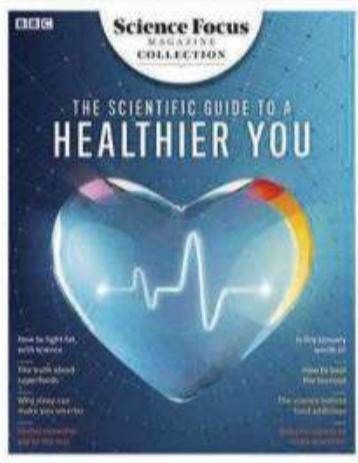
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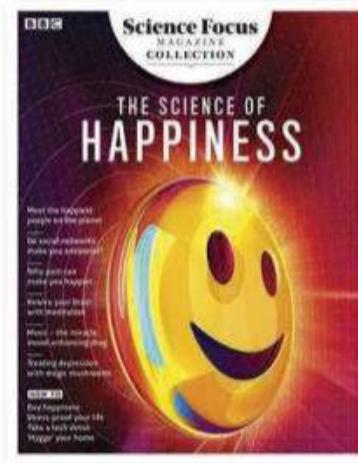
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Welcome



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When the world's population found its movements restricted by the pandemic, we witnessed how our planet's wild places can benefit from the absence of humans. The oceans saw noise levels plummet – thanks to a reduction in international shipping – which gave marine life a bit of a break. Restaurant closures led to less demand for fish and seafood exports, while fewer tourists meant decreased pressure on hotspots like coral reefs, beaches and mangroves.

But it's not all good. Our new, hygiene-conscious lives have caused a rise in single-use items, with some regions overturning previous bans on single-use plastic – that widespread scourge of the oceans. It remains to be seen whether there will be lasting environmental impact – good or bad – from the pandemic, but it strikes me that now is the perfect time to turn the tide on the damage we're doing to our oceans and to understand them better than ever before.

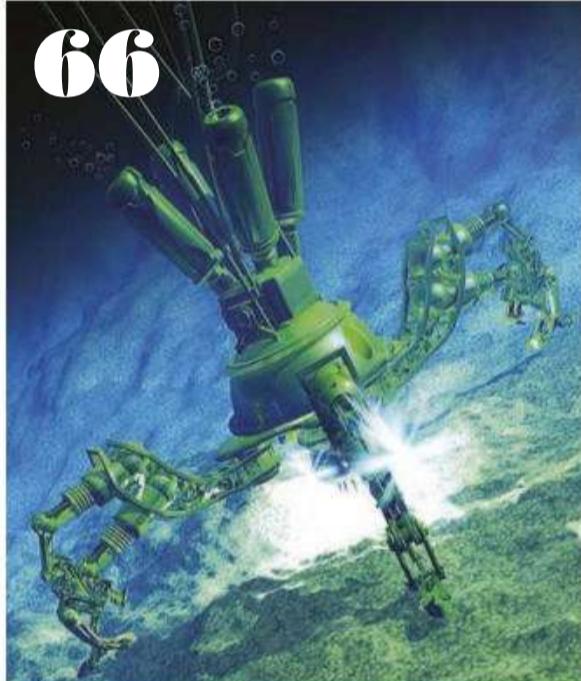
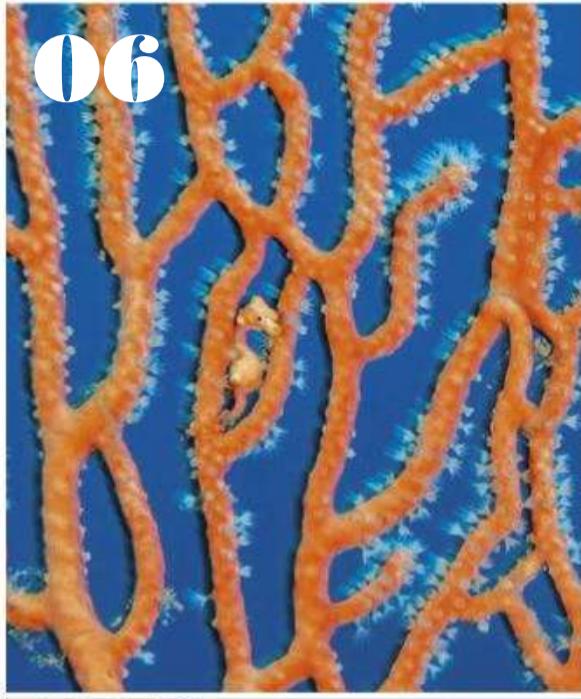
In this special edition, we find out about the projects that could help clear the plastics from our oceans. We also take a deep dive into the fishing industry, and investigate the new innovations that could ensure sustainable fishy dinners for the future. And if exploration is more your thing, then join us as we plunge into the bottom of the ocean to discover the wonderful life living within the inky depths and how we can protect it for years to come.

Enjoy the issue!

Alice

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What would happen if sea levels rose by 2m? How do sharks smell blood? Can corals recover from bleaching events? Do fish drink?





EYE OPENER

Hide and seek

WEST PAPUA,
INDONESIA

A tiny Denise's pygmy seahorse (*Hippocampus denise*) peeps out from its home in a sea fan (*Annella sp.*). It has the smallest home range of any fish and will stay on this gorgonian coral for the rest of its life. Measuring no more than 2.4cm, it's too tiny to fend off predators, so it has turned to camouflage instead, adapting its colour to blend in with the surrounding coral. Covering the seahorse's body are small bumps, called tubercles, which further aid its clever disguise, mimicking the polyps that make up the sea fan.

But don't be fooled by its small size. This pygmy seahorse is a master of stealth, sneaking up to within one millimetre of its unsuspecting copepod prey before striking.

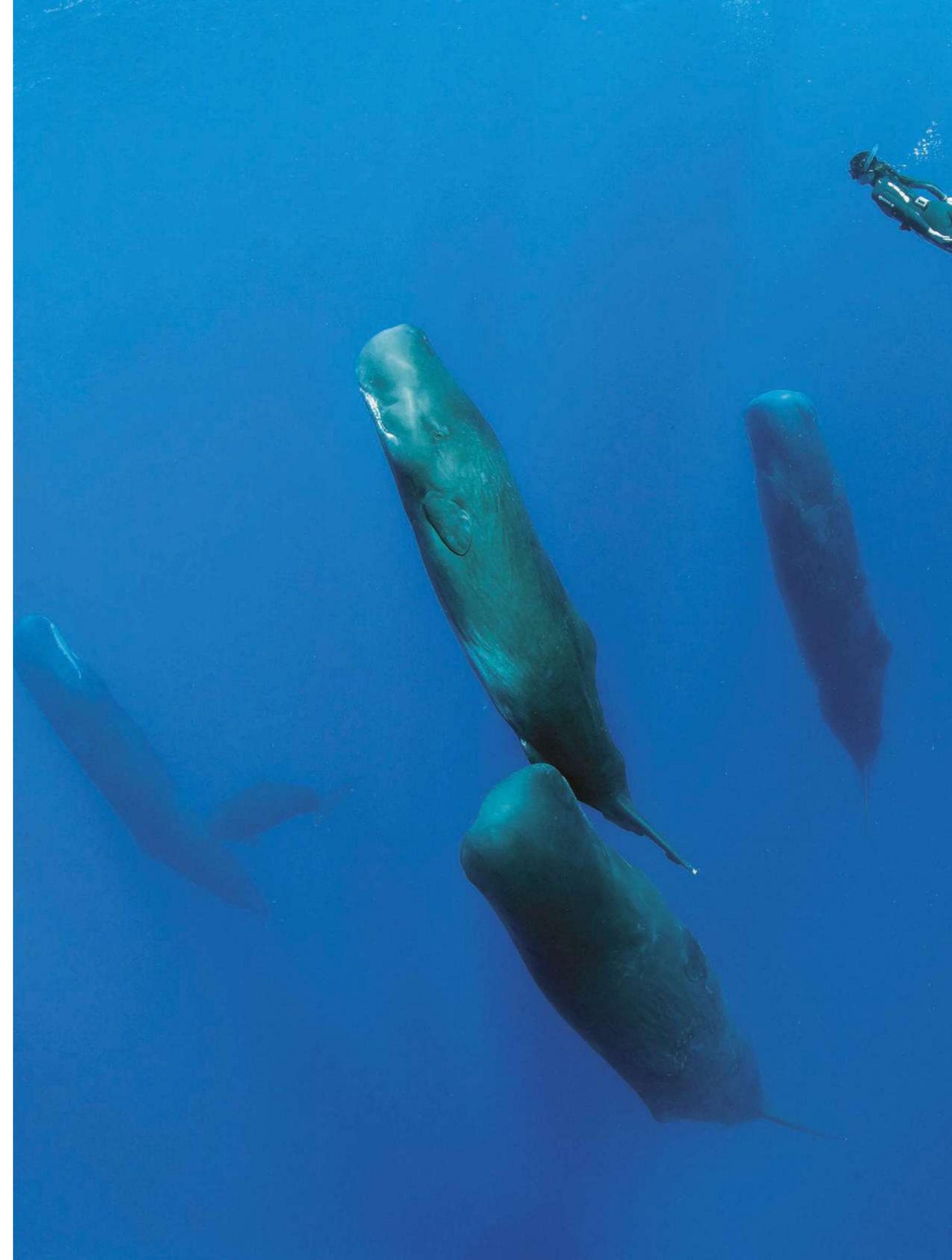
It is unclear what the sea fan gets from this arrangement, although it may turn out to be mutually beneficial as some copepods are parasitic and are known to infect gorgonians.

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EYE OPENER

Sleeping giants

DOMINICA,
CARIBBEAN SEA

When the planet's largest toothed predator decides to take a snooze, it can look pretty weird. Floating in a state of suspended animation, the sperm whale will sleep for 10 to 15 minutes at a time.

Inside a sperm whale's head is a large, oil-filled spermaceti organ, which scientists believe functions as an acoustic transducer – a kind of focusing lens for their echolocation equipment. But it also helps keep them neutrally buoyant, so they do not float to the surface or sink.

"The whales suddenly stopped a few metres under the surface and put themselves in a vertical position," photographer Franco Banfi recalls. "They stayed like that for several minutes, periodically expelling air bubbles from their blowholes."

The group pictured here are probably females, with perhaps some young males. Adult males prefer the solitary life outside of mating season.

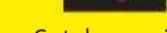
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HOW WE CAN SAVE THE OCEAN



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Worlds, One Planet*,
available now on
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Seven-tenths of the world is covered by the oceans. They put food on our plates, regulate the climate, and provide up to 50 per cent of the oxygen we breathe. But human activity is putting that at risk. On 25 September 2019, the Intergovernmental Panel on Climate Change presented a report on the oceans that made dire reading. It said that even if greenhouse gas emissions declined sharply and global warming was limited to less than 2°C, sea levels could still rise by 30 to 60cm by 2100. Plus, we're emptying the oceans of

animals, having passed the point of 'peak fish' in 1992 when total global catch began a relentless decline. A third of marine mammals are at risk of extinction. Our carbon emissions have made the oceans 30 per cent more acidic since pre-industrial times, threatening aquatic life in many ways. But many people are working to turn things round. "There are lots of solutions out there," says conservation scientist Dr Heather Koldewey, from the Zoological Society of London. "It is quite extraordinary, the power of good in the world." ➤

OCEANS AND HOW THEY CAN SAVE US

by DR HELEN SCALES

PART ONE

HERE ARE SOME OF THE
BRIGHTEST AND BEST
INITIATIVES THAT HOPE
TO SAFEGUARD OUR
OCEANS' FUTURE

THE SMART MACHINE THAT CATCHES PLASTIC AT THE SOURCE

Plastic particles have become ubiquitous in our seas. They have been spotted in remote areas of the poles and in the deepest ocean trenches.

While a number of projects focus on removing plastics from the seas, tech start-up Ichthion has developed a system for extracting plastic waste from rivers. Rivers play a big part in the plastic problem in the oceans, because they sweep tonnes of waste from land out to sea. "What we're doing hundreds of thousands of miles inland really does have an impact," explains conservation scientist Dr Heather Koldewey, who recently took part in an expedition that tracked plastic waste along the River Ganges.

Ichthion's Azure device sits on a river's surface and diverts floating objects towards the river banks, where a conveyor belt lifts them up and runs them past a camera. An artificial intelligence algorithm then recognises the shapes and colours of different plastics and packaging brands. This enables researchers to pinpoint where rubbish is coming from and what types of plastics are most common. "Without data, it's like fighting

against a problem that we don't understand," says Inty Grønneberg, CEO of Ichthion. The recovered plastic, up to 80 tonnes a day, is then sorted and sent off for reuse and recycling.

The first Azure systems are due to be installed later this year in Ecuador, where it's

hoped they will stem the flow of plastic heading towards the Galapagos Islands.

Another device that the Ichthion team is working on will attach to ships and filter plastic particles from the water, an idea inspired by basking sharks that sieve plankton through their gills.

Inty Grønneberg with part of the Azure system, which will sweep plastics from rivers without harming wildlife





BREEDING TOUGHER REEFS

Coral reefs are thriving ecosystems, with one-quarter of all marine species calling them home. But if average temperatures rise by 2°C by 2100, most of the world's reefs will be destroyed. Breeding 'super corals' could be one way of saving them from the climate crisis. In Australia, Prof Madeleine van Oppen is continuing the work she began a few years ago with coral biologist Ruth Gates, who died in 2018. She, and other teams of researchers, are trying different techniques that fall under the umbrella of 'assisted evolution', ranging from selective breeding to gene editing.

Some species of coral are naturally better able to cope with heat, and there are

already promising results from cross-breeding these tougher corals with other species to produce heat-tolerant hybrids. Meanwhile, scientists are hunting for the genes that give some corals their heat tolerance. Ultimately, the aim could be to replant reefs with hardy, lab-grown corals.

Conservation scientist Dr Heather Koldewey, from the Zoological Society of London, warns that we don't have time to conduct decades of research but urgently need to assess which solutions are most viable, so we're ready to act. But until countries cut greenhouse gas emissions, "everything else we're doing for coral reefs is just buying time," she says. ➤

ABOVE Prof Madeleine van Oppen (right) and Line Bay are creating tougher corals that could cope with changing ocean conditions

RIGHT A researcher prepares coral samples in the lab



SHARK EYE IN THE SKY

In Australia and South Africa, shark nets are often deployed in coastal regions to reduce the likelihood of shark attacks – not by putting a barrier between humans and sharks, but by deliberately killing thousands of sharks a year. The theory is that fewer sharks mean fewer attacks. However, as top predators, sharks are an important part of the ecosystem, and many species are already threatened. The nets can also trap other vulnerable marine life, including stingrays, dolphins and turtles.

Project Airship could provide a cost-effective, zero-impact alternative means of keeping bathers safe. Project Airship uses tethered blimps that are equipped with motion-sensitive cameras to keep an eye on coastal waters. According to founder Kye Adams, these blimps will keep going all day, as opposed to coastguard-driven drones that can only run for around 20 minutes.

During two test seasons in Australia, Adams deployed ‘analogue sharks’, otherwise known as human freedivers, into the sea. He was pleasantly surprised by how well the camera detected the divers swimming underwater with their arms stuck out to imitate a shark’s pectoral fins. The next step will be to use artificial intelligence to automatically detect real sharks. Ultimately, the airships could be an option to reassure swimmers and surfers that it’s safe to go into the water, rather than killing sharks by launching culling campaigns and setting up shark nets.

Kye Adams
hopes that his
Project Airship
will stop shark
culling and the
deployment of
shark nets



PAUL JONES/UNIVERSITY OF WOLLONGONG, GETTY IMAGES



POLICING POACHERS FROM SPACE

Until a few years ago, it was almost impossible to track illegal fishing activity that was taking place out in the open ocean. What happened beyond the horizon, stayed beyond the horizon.

Since 2016, the Global Fishing Watch has been keeping an eye on the oceans from space. The collaboration between internet giant Google, the conservation group Oceana and satellite technology experts SkyTruth, makes it much harder for vessels to hide what they're up to.

The technology is based on the tracking devices that large boats must carry to broadcast their location, speed and course in order to avoid collisions with other vessels. The Global Fishing Watch team used this publicly-available information to teach computer algorithms what different types of fishing looks like. For example, long-lining boats work

over and over straight stretches of water, while trawlers crawl around more haphazardly. Now, the system analyses 60 million data points each day to identify the telltale fishing patterns of more than 65,000 vessels. The fishing activities are then posted in near real time on an interactive, online map that anyone can access and download. Already, governments are using the data to combat illegal fishing inside marine reserves, while researchers are drawing up strategies for making legal fishing more sustainable.

The system can even identify fishing vessels that are trying to dupe the system. The algorithms detect when several vessels use the same identification number, or when someone tampers with the onboard GPS and the vessel's broadcast location doesn't match the whereabouts of the satellite that received the data. ➤





SEND IN THE ROBOTS!

The deep sea is the planet's biggest habitat, but we still know so little about it. With emerging threats such as deep-sea mining, it has become increasingly urgent to study this habitat so we can find out what species live down there and what impact our actions will have.

The problem is, it's incredibly difficult to explore the ocean depths, but technological innovations, including fleets of diving robots known as autonomous underwater vehicles or AUVs, are helping us make this a possibility. Equipped with high resolution cameras, AUVs are the powerful eyes that allow us to glimpse the environment beneath the surface. The only snag is that somebody has to pore through the footage afterwards. "It's astronomical how long it takes to analyse imagery," says Prof Kerry Howell, a marine ecologist from Plymouth University. Howell leads the Deep Links project, which recently tested artificial intelligence as a way of speeding up the process.

Her team took a dataset of 150,000 images collected by one of the UK's AUVs, called Autosub6000, from a dive it made to more than a kilometre deep on the Rockall Bank in the Atlantic Ocean. PhD student Nils Piechaud got the unenviable job of examining 1,200 of those images and identifying 40,000

animals from more than 100 species. Using those images, he then trained Google's TensorFlow – a deep learning algorithm – to identify deep-sea animals. The algorithm's performance was then tested using other images it hadn't already seen. "For some species, it does very well," says Howell. Over 90 per cent of the time, the algorithm correctly spotted xenophyophores, organisms that look like croquet balls made of honeycomb.

It's early days, but Howell is convinced that algorithms will assist researchers with mind-numbing tasks and help unlock the potential of autonomous technologies. "The brilliant thing about artificial intelligence and computer vision is that it's consistent,"

says Howell. Unlike humans, algorithms don't get tired, or make unpredictable mistakes.

Of course, machines aren't always right, but their bias can be quantified and removed from the data – something that's impossible with the wandering minds of humans.

ABOVE Boaty McBoatface is an AUV that explores the deep sea with the British Antarctic Survey

BETWEEN This deep-water starfish was spotted by Plymouth University's AUV and has only been seen a handful of times

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PART TWO

DRUGS, FOOD AND OXYGEN... HERE IS WHAT WE STAND TO LOSE IF WE FAIL TO PROTECT OUR OCEANS

Corals, like the ones spawning here, are a promising source of new drugs

AN UNOPENED MEDICINE CHEST

Modern medicine is becoming threatened by antibiotic-resistant infections such as MRSA. With lifesaving drugs losing their efficacy, some experts warn of a return to the Dark Ages if this continues.

As a consequence, an urgent search is underway for new medicines to battle against resistance, and one place people are looking is in the oceans. "Sponges and corals are the most promising sources of natural products that have medical properties," says Prof Kerry Howell, a marine ecologist from Plymouth University. That's because these

animals are commonly colonised by bacteria that have evolved chemicals to defeat and kill each other, making the ideal basis for antibiotic drugs.

As a deep-sea biologist, Howell is among the first to know about any new molecules discovered in the oceans. Howell and her colleague Mat Upton, a microbiologist also at Plymouth University, have already uncovered at least one molecule extracted from deep-sea bacteria that seems to be effective against MRSA.

Howell admits that she originally became interested in bioprospecting as a way of persuading people to

care about deep-sea species. "If you don't care about the deep sea just because it's wrong to destroy species and habitats, then at least care about it because it might actually save your life," she says.

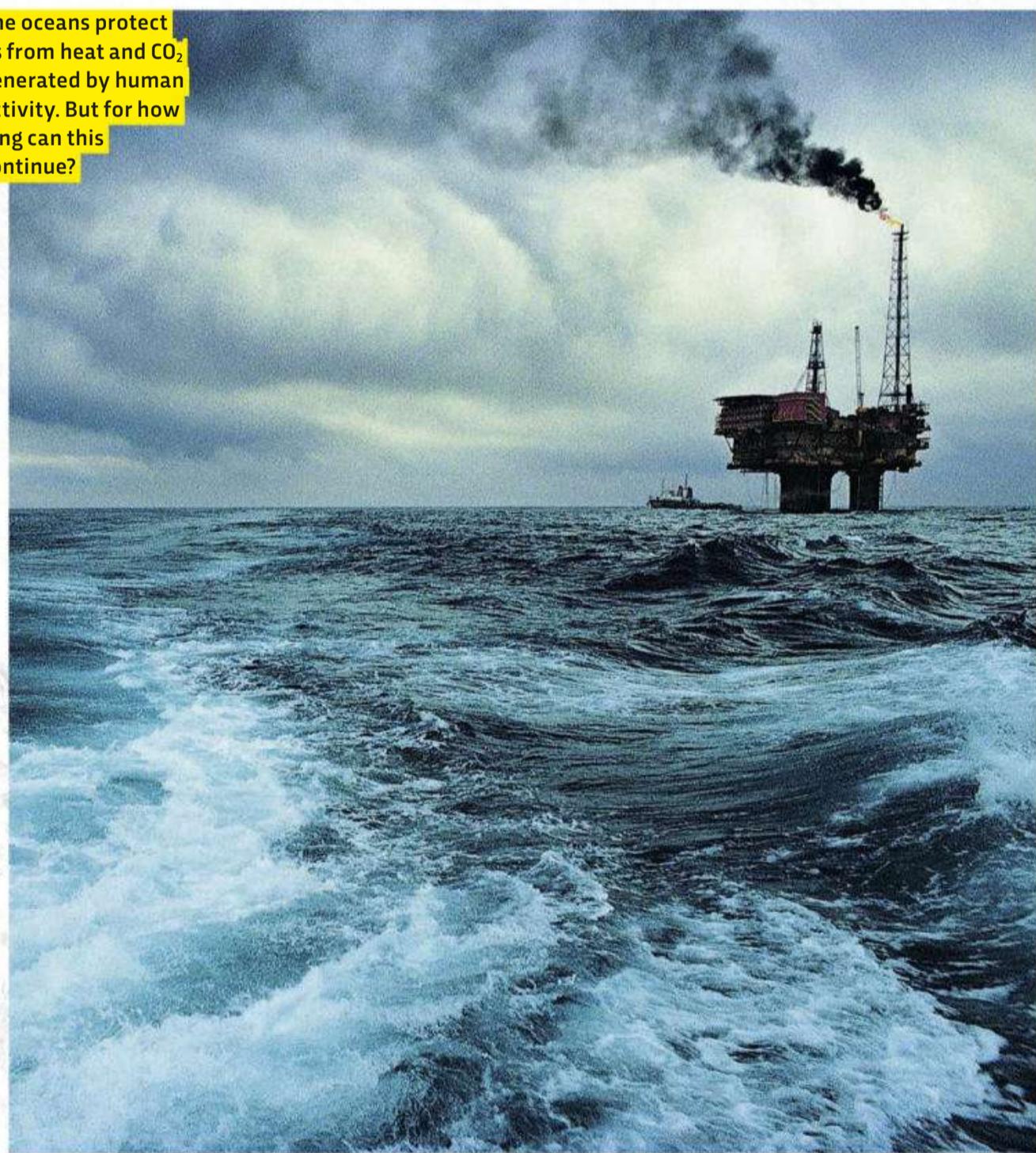
It's not only antibiotics that are being found in the oceans. Painkillers have been produced that are based on the toxins of deadly, tropical cone snails. Meanwhile, a Caribbean sponge has yielded various antiviral and anti-cancer drugs, including cytarabine to treat lymphoma and leukaemia, and aciclovir used against shingles, chickenpox, cold sores and herpes. ➤

OCEANS THAT SOAK UP HEAT AND CO₂

Without the oceans, the climate crisis would already be far worse. This huge volume of water has absorbed more than 90 per cent of the heat from the warming atmosphere, and soaked up many gigatonnes of carbon dioxide (one gigatonne = a billion tonnes).

A recent study calculated that between 1994 and 2007, the oceans absorbed close to one-third of all the CO₂ emitted by human activities. "The oceans have shielded us from the heat, they've shielded us from the carbon dioxide," says Dan Laffoley, from the International Union for the Conservation of Nature. "If the ocean hadn't been there, global surface temperatures would be over 30°C warmer."

The oceans protect us from heat and CO₂ generated by human activity. But for how long can this continue?



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He describes the oceans as a comfort blanket that has been keeping conditions just right for life on Earth. But while their colossal absorption of carbon and heat helps to stave off the climate crisis, it causes other problems beneath the waves. The oceans themselves are noticeably warming and are becoming more acidic, and as temperatures rise the oceans are losing oxygen.

And this spells bad news for all sea life, which will find it harder to breathe and survive. The shifting chemistry of the oceans makes life especially tough for corals, clams, plankton and other organisms with shells or skeletons made of calcium carbonate, as this substance begins to dissolve as pH drops.

THE LUNGS OF THE PLANET

We should all be thankful for the existence of phytoplankton. Multitudes of these tiny organisms float through the oceans, harnessing energy from the Sun via photosynthesis, and in the process producing roughly half of all the oxygen in Earth's atmosphere (the rest comes from land plants).

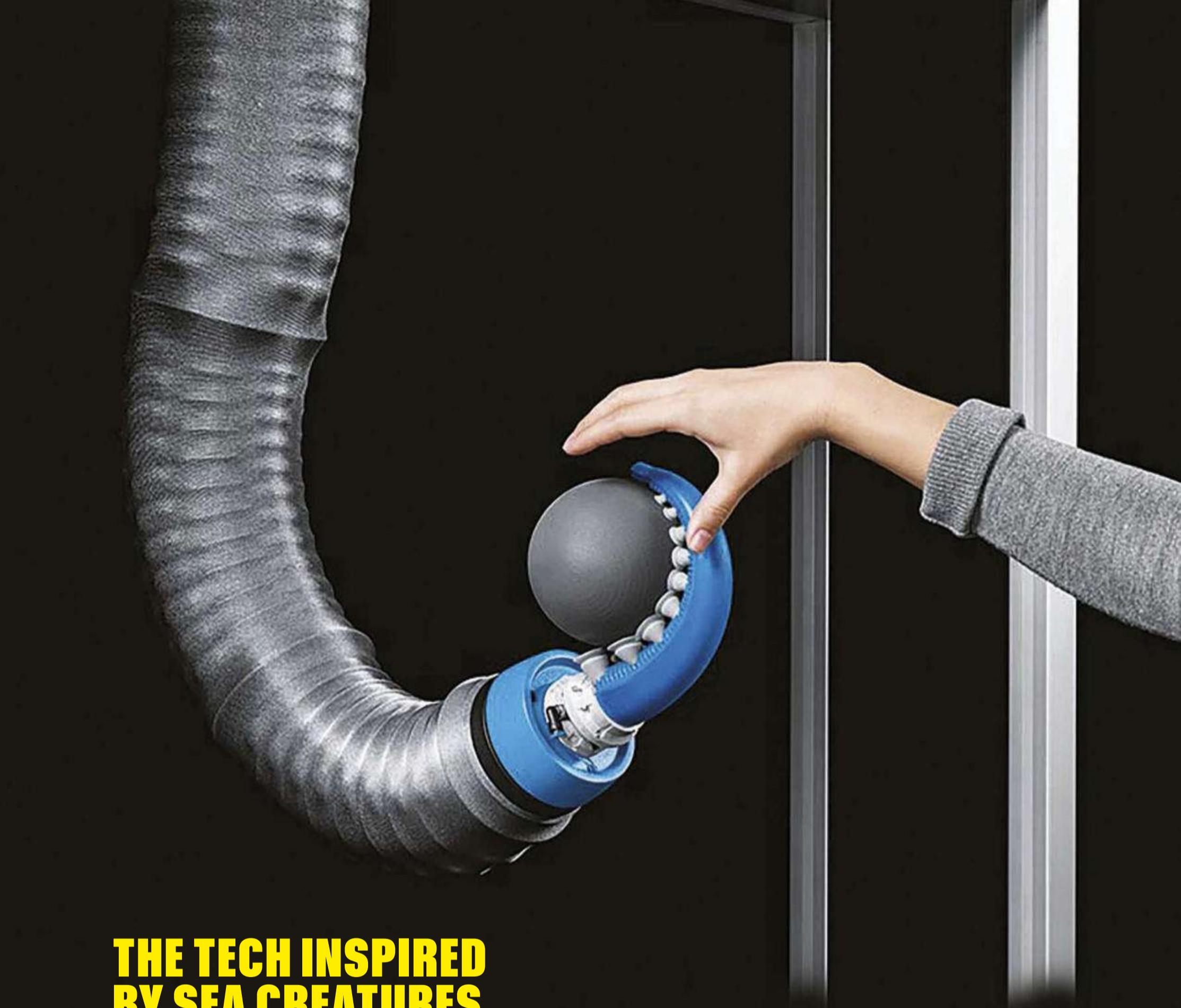
Especially important is a type of cyanobacteria, or blue-green algae, called *Prochlorococcus*. What they lack in size – 10 of them could fit across the width of a red blood cell – they more than make up for in numbers, and are probably the most abundant photosynthetic organisms on the planet.

"They exist in such numbers that they're measured in octillions, which I think is 10²⁷, a ridiculously massive number," says Dan Laffoley, from the International Union for the Conservation of Nature.

Prochlorococcus specimens were first isolated from water collected from the Sargasso Sea in 1986, by oceanographer Sallie Chisholm from the Massachusetts Institute of Technology. In 2019, she was awarded the \$750,000 Crafoord Prize for her groundbreaking discovery and ongoing study of the vitally important cyanobacteria.



Enjoy breathing? You can thank these *Prochlorococcus* specimens



THE TECH INSPIRED BY SEA CREATURES

This robot built by German company Festo was inspired by octopus arms

Many scientists and engineers have been inspired to develop useful new materials, structures and technologies based on the things that live in the oceans. For example, instead of clunky, metal robots, we could one day see soft-bodied machines inspired by the flexible arms of octopuses. Octopuses' amazing ability to change the colour and texture of their skin to instantly match their surroundings is also being investigated for use as military camouflage.

Inspiration from the oceans can come from the humblest animals. For example, researchers wanted to know how mussels stay attached to rocks, even when they are wet and being pounded by waves. It turns out that the molluscs secrete a special type of waterproof glue, which medical researchers are now using to develop surgical adhesives to use in intricate procedures, such as operating on unborn babies.

A relative of mussels – the limpets – posed another question that was only recently answered: how do these common shoreline molluscs spend so much time scraping algae from rocks without smashing their teeth? Their secret lies in the intricate nanostructure of their gnashers, which makes them the toughest known biological material. If a limpet wanted to, it could chew its way through a bulletproof vest. Their tiny, resilient teeth could be replicated and used to our advantage for manufacturing tough materials.

Sea urchins take the concept of impressive dentistry a step further with their self-sharpening teeth. Their teeth are made of layers of calcium carbonate crystals and organic material with specific weak points that snap, leaving a razor-sharp edge. If materials scientists can mimic that ability, we could find ourselves using urchin-inspired, self-sharpening scissors and knives. ➤



AN IRREPLACEABLE SOURCE OF FOOD

According to the World Wide Fund for Nature (WWF), approximately three billion people rely on seafood as their number one source of protein. Just under half of the fish we eat comes from wild animals caught in the oceans, with the rest coming from fish farms. Besides the familiar fish and shellfish, the oceans provide something else that reaches into our diets and daily lives, often without us knowing it. Each year, at least 25 million tonnes of seaweed are farmed.

Sometimes you'll see it as the nori wrapped around your sushi rolls, but a lot of it is used to make industrial products, including alginates and carrageenans, which end up in all sorts of items. Shampoo, toothpaste, pet food, ice cream, processed meats, vegetarian hot dogs, beer, shoe polish, air fresheners and fire extinguishers can all contain chemicals derived from seaweed.

Seaweed farming has traditionally been carried out in Asia, and now

other countries including the UK and US are catching onto the benefits. Not only is seaweed considered a 'superfood' that's rich in iodine, calcium and amino acids, but it can be sustainably farmed and is carbon-neutral, absorbing carbon dioxide and mopping up excess nutrients from the sea. Seaweed can be used to create biofuels, while research suggests that cattle reared on seaweed-based feeds produce less methane, a potent greenhouse gas.



by DR HELEN SCALES
(@helenscales)

Helen is a marine biologist, broadcaster and author. Her next book, *The Sea Beneath Us* (£16.99, Bloomsbury Sigma), will be out in February 2021.

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IT'S TIME FOR ACTION

Given everything they provide and all the ways they make planet Earth habitable, it's crystal clear that the oceans urgently need safeguarding. Establishing marine reserves where all damaging activities are off limits – particularly fishing – is a major win-win for the oceans and for us: ecosystems become healthier and potentially more resilient to climate change, while fishing is boosted by the eggs and larvae of species that spill out from these thriving oases.

Currently, around 8 per cent of the world's ocean area has some level of protection inside marine reserves, although many are considered to be good on paper, but not well-enforced.

The European Commission claims that 10.8 per cent of European seas are protected, but a recent World Wide Fund For Nature (WWF) report concluded that properly managed reserves only cover 1.8 per cent. A global target to protect 10 per cent of the oceans by 2020

looks to be within reach, but conservationists and scientists are demanding more. In 2016, members of the International Union for the Conservation of Nature (IUCN), including 1,400 governments, NGOs and indigenous communities, voted overwhelmingly in support of a new target: protect 30 per cent of the oceans by 2030. This will help support fisheries, encourage biodiversity and safeguard traditions linked to the oceans.

"There's no scientific publication that supports the current policy of protecting 10 per cent," says the IUCN's Dan Laffoley. Science is telling us that the minimum needed is one-third protection of the oceans, or more. And it's not just about marine reserves but also what happens outside them. "If we are to have a sustainable ocean," says Dr Heather Koldewey, a senior advisor at the Zoological Society of London. "It has to be a combination of protection combined with sustainable management of the rest." **SF**



THERE AREN'T PLENTY MORE FISH IN THE SEA

Decades of poor fishing practices may spell the end of fish as food. But it's not the end of the line yet, as new innovations could help reverse the damage

by DR HELEN SCALES

GETTY IMAGES



A

reef shark slides past, an arm's length away, then another. And moments later a third. These sleek hunters pay me no attention and seem accustomed to having people nearby. Scuba divers like me flock to visit the sharks and other marine life flourishing around the remote islands of Palau in the western Pacific Ocean. This special place offers a glimpse of how things used to be before human activities began emptying the oceans.

Palau remains a rare underwater wonderland, in part because the government takes marine protection seriously. In 2015, the country's president, Tommy Remengesau Jr, declared 80 per cent of the nation's waters off-limits to fishing. This is one of a new generation of marine reserves. More recently, in August 2016, Barack Obama, who was then the US president, announced a huge expansion of Hawaii's Papahānaumokuākea marine reserve. It's a massive 1.5 million square kilometres – about the size of Spain, France and Germany combined.

The drive to set up these reserves, plus various other measures to protect the seas, stems from growing awareness that the oceans are in trouble. It's becoming clear there are no longer plenty more fish in the sea.

In 2006, a prominent group of marine scientists published a paper in the journal *Science* scrutinising the state of the oceans around the world. From their survey of the abundance and diversity of marine life emerged a headline-grabbing forecast: by 2048, all existing fish stocks could have collapsed.

Not all experts agreed on that date, which assumes the present rate of collapse will continue at its current rate – already a third of all fish stocks

"FROM THE SURVEY EMERGED A HEADLINE-GRABBING FORECAST: BY 2048, ALL EXISTING FISH STOCKS COULD HAVE COLLAPSED"

have collapsed since 1950. Others have re-analysed the same data and pushed the date to the 2070s or even 2100s. Still, it's a dire prognosis for fisheries that feed billions of people worldwide.

And now, 14 years later, there are very few signs of improvement. "The picture painted in that paper is largely true," explains Prof Callum Roberts, a marine conservationist from the University of York. "Wild seafood stocks are still declining rapidly."

A major study in 2016, published by marine biologist Dr Daniel Pauly and colleagues from The Sea Around Us project, warned that the world has probably already passed 'peak fish'. A team of 400 researchers gathered data from small-scale, recreational and illegal fisheries that normally remain under the radar. They showed that the total seafood catch, comprising all the fish, shellfish and other invertebrates caught from the seas worldwide, is far higher than official figures suggest. This may appear to be good news: if more seafood is being caught, maybe the oceans aren't as empty after all. Far more worrying, though, are the trends over time. It had been thought that since the 1990s, the global catch had levelled off and stayed roughly the same year-on-year. These latest, more complete figures indicate that global fisheries peaked at 130 million tonnes in 1996. Since then, catches began to drop by 2 per cent every year. Despite expanding fleets and advancing technologies, fisheries are unable to catch as much as they used to.

BELOW Fishing lines and nets lost at sea do not readily break down, so they can continue trapping animals for years

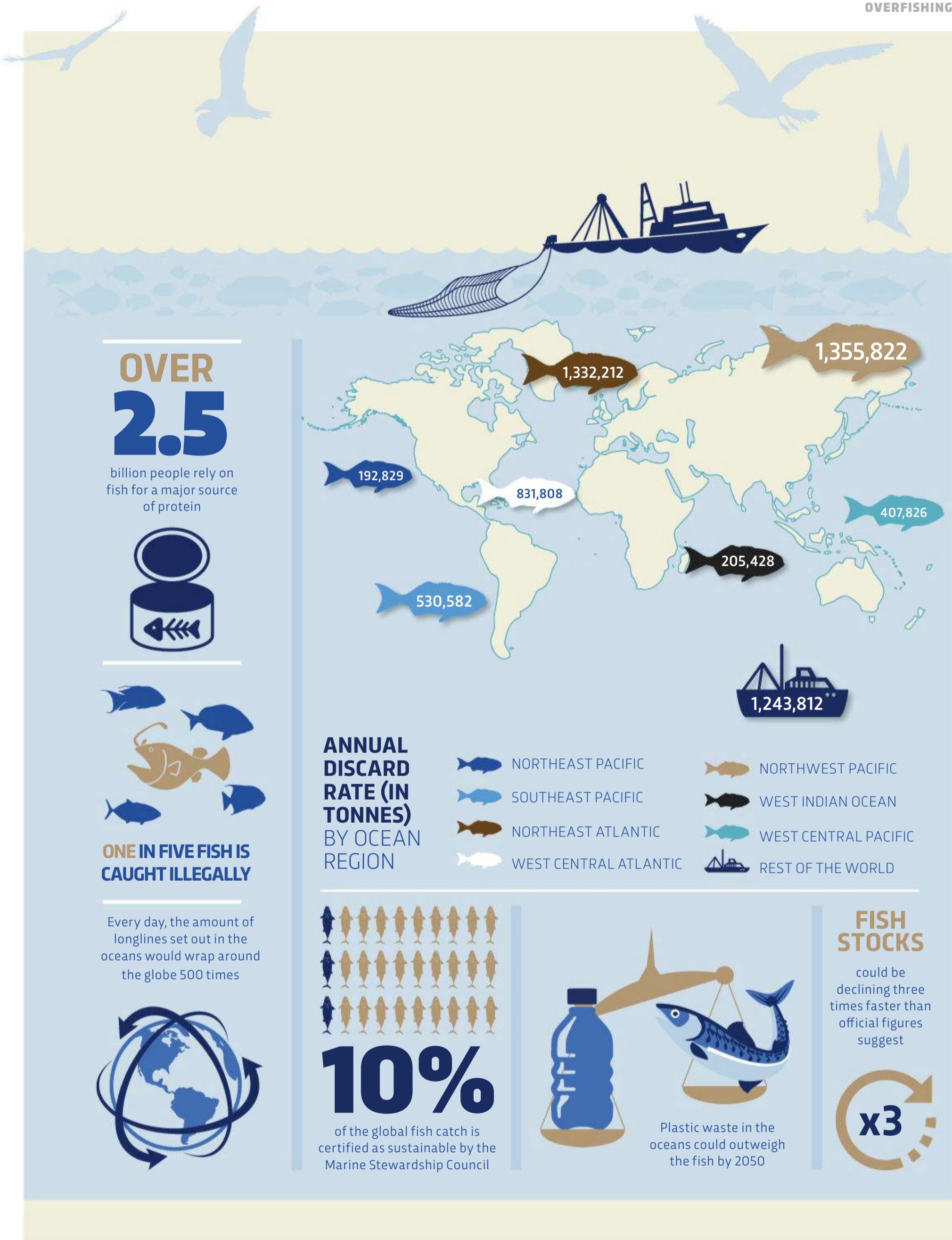
WHERE HAVE ALL THE FISH GONE?

Behind the global fishing crisis lies a catalogue of problems. First and foremost, there are simply too many fishing boats chasing fewer and fewer fish. This is partly because of financial subsidies and other perks keeping fisheries afloat. Governments provide cheap fuel for boats, tax rebates, low-interest loans and other measures to maintain fisheries that would otherwise become unprofitable and fold as fish become scarce.

Fishing also physically damages the marine environment. Trawlers and dredgers scrape heavy nets across the seabed, smashing delicate, centuries-old habitats. Huge quantities of unwanted sea life are caught that have no market or quota. This so-called bycatch is usually thrown straight back into the sea, already dead or dying.

Added to all this are convoluted impacts of pollution and climate change. Warming seas are driving certain species towards the poles, rearranging ecosystems and causing coral reefs to bleach and die, while carbon emissions are making oceans more acidic, which weakens shellfish and





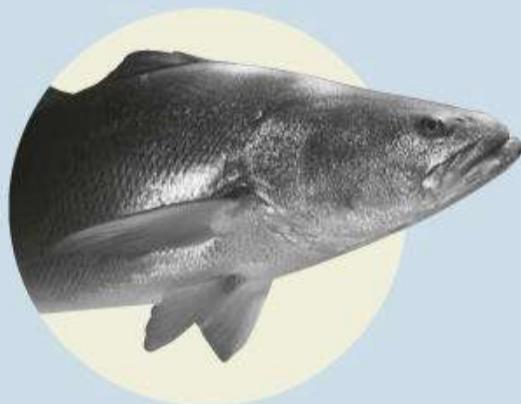
THE BIGGEST LOSERS

Some species are more sensitive to pollution and fishing than others...



ANGEL SHARK

The angel shark was once common from the North Sea to the Mediterranean. As it lives on the seabed, it is taken as bycatch by trawlers and has been almost completely wiped out. Now it only lives around the Canary Islands.



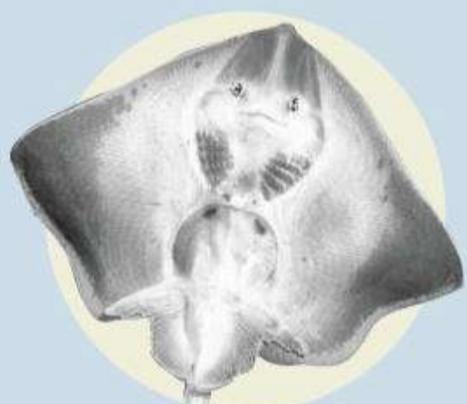
TOTOABA

Illegal fishing is driving the totoaba to extinction in its native range in the Gulf of California. Its swim bladder, an organ that regulates buoyancy, is worth up to £6,500 a piece in China to make into soup.



WHALE SHARKS

In 2016, the whale shark was listed as endangered by the World Conservation Union because its numbers have halved in the last 75 years. It only becomes sexually mature at between 20 and 30 years old, so populations take a long time to recover.



COMMON SKATE

With a name that's become sadly ironic, the common skate is critically endangered in the Atlantic and Mediterranean, and extinct in the Baltic. Along with some other skate species, its large size makes it vulnerable to being caught in nets.



EUROPEAN EELS

Numbers of young European eels have crashed by up to 95 per cent in the last 30 years. Declines are blamed on habitat loss, pollution and barriers to migration. Eels are born in the Sargasso Sea, before migrating across the Atlantic and up into rivers and streams, where they mature.



Certain fishing methods indiscriminately plunder the seas, sometimes catching vulnerable species, such as sharks, dolphins and turtles

► alters fishes' hearing and behaviour. To make matters worse, fish that end up on our plates are also becoming filled with fragmented plastic. Fixing all these problems is undeniably an immense task; they don't act in isolation but together, often worsening each other. Nevertheless, effective solutions are already available.

SAVING THE SEAS

Marine reserves are a proven way of restoring fish populations. By excluding fishing from particular areas, reserves allow marine species to recover from previous exploitation.

A 2009 study brought together hundreds of papers on the subject and showed that reserves tend to work well in both tropical and temperate waters. Reserves dramatically boost the density of marine species, by 166 per cent on average; species diversity also goes up by around 20 per cent. Reserves also keep habitats healthy and help make ecosystems more resilient to climate change. A well-known example comes from the Philippines. In the 1980s, 10 per cent of the coral reefs around Apo Island were closed to fishing. Twenty years later, the total quantity of the two main targeted fish groups, surgeonfish and jacks, had tripled inside the reserve. Benefits also spill out as adult fish and larvae move into unprotected areas, replenishing the wider seascape. The fishermen of Apo saw a 50 per cent increase in their catches outside the reserve. Similar stories are coming in from reserves around the world.

The portion of the oceans that falls within some



To find out more about sustainable fish visit goodfishguide.org. You can also download the *Good Fish Guide* as a PDF or as an app for iOS and Android.

"CONSUMER CAMPAIGNS HAVE MADE A BIG DIFFERENCE TO THE WAY SUPERMARKETS THINK ABOUT SOURCING THEIR FISH"

form of marine reserve is gradually rising. A major obstacle, though, is enforcement. Many countries lack resources for patrols, especially in very large, remote reserves. "Here you have an activity that becomes invisible when it gets beyond the horizon," says Jackie Savitz, from the non-profit group Oceana. She's heading up an initiative to make fishing more visible.

Global Fishing Watch (globalfishingwatch.org), which launched in September 2016, is a free online tool showing where fishing is happening anywhere in the world. The project uses data from Automated Information Systems (AIS) required on many watercraft over a certain size to avoid them crashing into each other. AIS broadcasts public information via satellite on the vessel's location, heading and speed. These data are being mined to detect which vessels are fishing, where and when.

Oceana brought Google to the party, to help analyse the big data generated by AIS devices and detect the characteristic movements of fishing. The Global Fishing Watch website currently tracks over 35,000 fishing vessels in near real-time; typically data go online around 72 hours from the present. It's

by DR HELEN SCALES
(@helenscales)
Helen is a marine biologist, broadcaster and author. Her next book, *The Sea Beneath Us* (£16.99, Bloomsbury Sigma), will be out in February 2021.

hoped governments will use the website to enforce sustainable fisheries regulations, such as closed seasons and marine reserves. Kiribati, a small nation located in the Pacific Ocean, has already used the data to fine a commercial vessel \$1m for illegally fishing inside the Phoenix Islands Protected Area.

Technology is also being applied to deal with bycatch. The conservation group WWF runs Smart Gear, a competition to develop new ways to stop unwanted species being caught. Winners in 2014 included Super Polyshark. These pellets of slow-release non-toxic, biodegradable shark repellent are inserted in the bait that's used on longline hooks. Tests show they reduce the number of sharks that go for the bait and get snagged. Other devices include scarers to reduce seabird deaths, and trapdoors in trawl nets that let turtles and cetaceans escape.

Back in Palau, studies are underway to limit bycatch in the 20 per cent of their national waters where fishing continues. The Nature Conservancy is testing different types of hooks in the tuna longline fishery to reduce the bycatch of sharks and turtles, species highly valued by divers. Every living shark in Palau is worth up to \$2m a year to the dive industry.

RECONNECTING WITH YOUR FISH

Seeing supermarket shelves still stocked with seafood, it can be difficult to make sense of reports of emptying seas. It's true that management successes have allowed some collapsed stocks to recover. In the 1970s, North Sea stocks of herring dramatically collapsed. "After a moratorium on fishing, together with some excellent management approaches, they've rebuilt the stocks," says Roberts. However, seafood supplies today are largely maintained by fishing in distant waters. Imports account for 90 per cent of seafood eaten in the US and around 60 per cent in Europe. This puts mounting pressure on other regions like West Africa, where there is little supervision to prevent overfishing and habitat loss.

This widening gap between plate and ocean makes it more important than ever for us all to care about where our seafood comes from. "Consumer campaigns have made a big difference to the way supermarkets think about sourcing their fish," says Roberts. More seafood is being certified as sustainable through eco-labelling schemes and awareness is growing over issues of bycatch and damaging fishing techniques. Plus, shoppers can easily check their seafood while in the supermarket by using apps such as the *Good Fish Guide*. "The more people who come into shops and say that this matters to me, the more likely it is that supermarkets will take note," Roberts adds. **SF**

FROM THE MAKERS OF

BBC
Science Focus

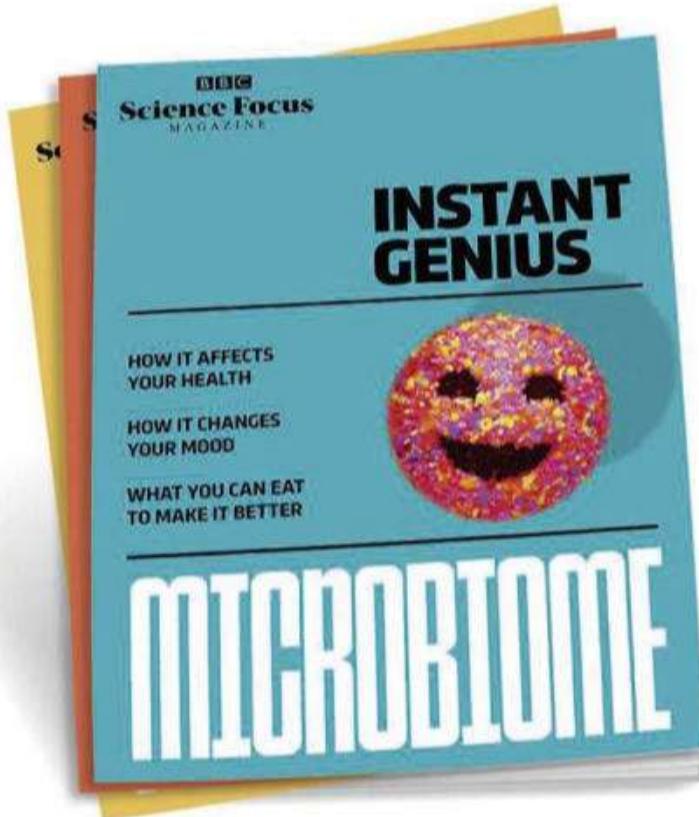
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WHAT IF

WE BANNED
FISHING?

WORDS: HAYLEY BENNETT

ILLUSTRATIONS: JASON RAISH

FISHING DAMAGES ENTIRE ECOSYSTEMS AND POLLUTES OUR OCEANS. SO WOULD WE BE BETTER OFF WITHOUT IT?

On average, we each eat more than 20 kilograms of fish per year. Worldwide, between 1961 and 2016, fish consumption increased faster than meat consumption, and grew twice as fast as the human population.

All of these fishy dinners have depleted marine fish stocks to a point where a third of global fish stocks are now classed as 'overfished', meaning that if we continue fishing

at the same levels, these populations will decline. Most of the rest are being exploited at the maximum levels that can be sustained without long-term decline. Fishing also has negative impacts on non-food species in the ecosystem, and pollutes the waters with fishing waste. Temporary fishing bans may help to alleviate some of the worst impacts, but what would happen if we banned fishing altogether? ➤



Watch Cornwall: This Fishing Life, available now on iPlayer. bit.ly/fishing_life

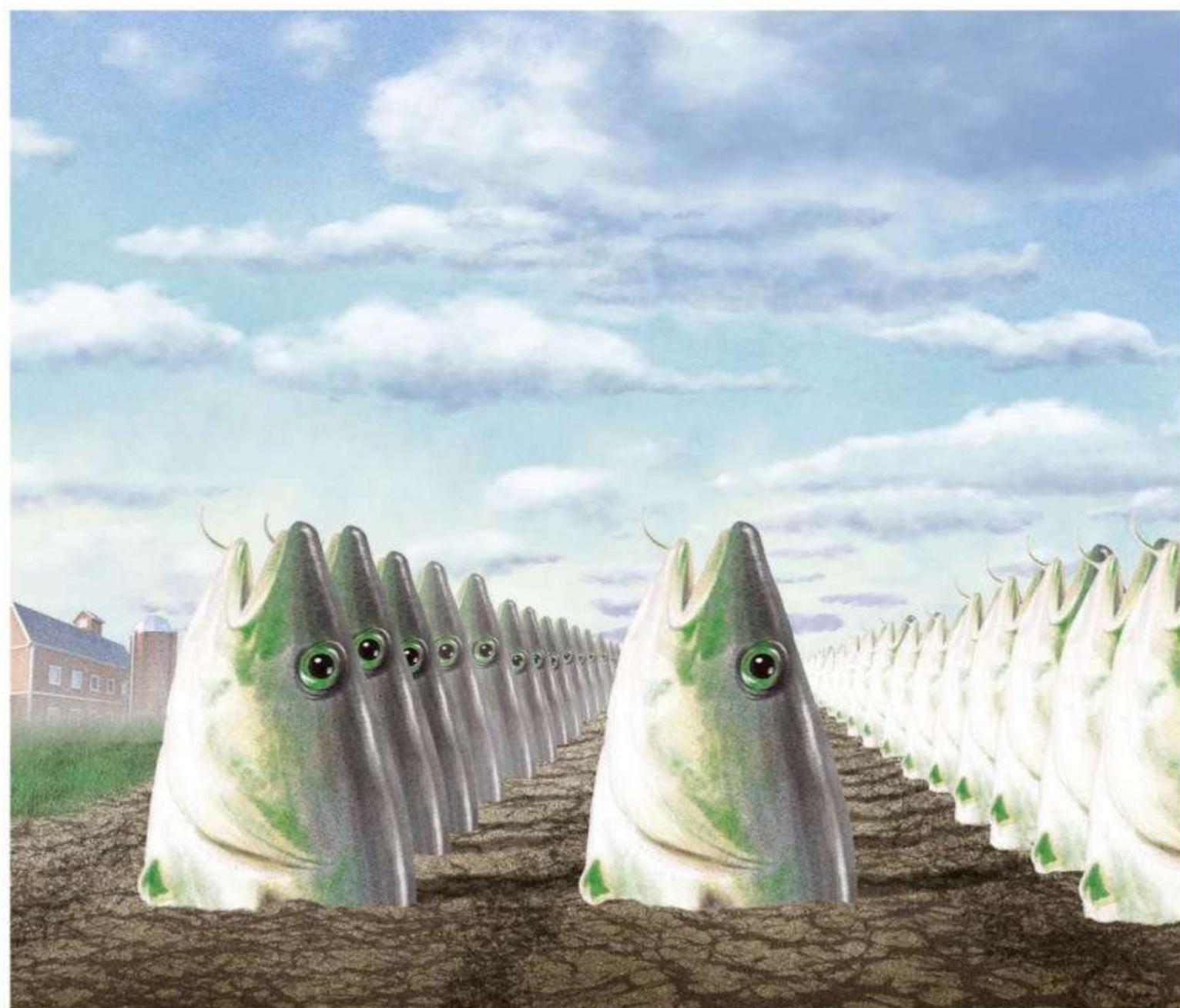
1

Millions would struggle to eat and earn enough

Around the world, 40 million people earn their living directly from catching wild fish, while another 19 million are employed in aquaculture – fish-farming or growing seafood in controlled conditions such as sea pens and cages, lochs and ponds. But these figures may hide the true extent of the planet's dependency on fishing. Along coasts, estuaries and coral reefs, millions of small-time fishers make a meagre wage from fishing, or catch fish just to put food in their families' mouths. Some fishers don't make the stats, and neither do their catches. "A lot of the small-scale catches are distributed in informal markets, where they're not recorded," says marine ecologist Dr Steven Purcell at Southern Cross University in Coffs Harbour, Australia. His own studies suggest that 71 per cent of those fishing for *Trochus* sea snails in the Samoan islands eat them themselves or give them away to friends and neighbours. Seafood is a major source of protein across Southeast Asia and islands in the Indian and Pacific Oceans. So while in Europe or the US we could eat more meat or soy products to make up for lost protein, a fishing ban could lead to food scarcity in communities with little land-based farming.

We can also envisage a black market developing for fish, as there currently is for beluga caviar in the US, where it's banned. Eggs from the endangered beluga sturgeon are thought to be flown in privately to top Manhattan chefs. In the case of a total fishing ban, think less about caviar, more about ordering canned tuna from dodgy websites.





2

Seafood farms could step up to meet demand

Aquaculture already produces nearly half of the seafood we consume (or more, if you include seaweed), and we'll have to increase that if we are to avoid decimating wild fish stocks. Under a fishing ban, aquaculture could be our only source of seafood, meaning that, initially, we'd be eating a lot of Atlantic salmon – by far the most farmed fish across Europe. “[Wild] fisheries allow you a diversity of products that aquaculture would probably take many years to get to,” says Dr Sofia Franco at the Scottish Association for Marine Science. But she hopes to see a wider range of farmed seafood on the menu in future, as expertise in different species and farming systems develops. Until now, production has been largely in farms open to the sea, rivers, or lochs. Newer, land-based systems, such as tanks with recirculating

water, could reduce pollution and damage to aquatic environments compared to the older systems.

But could you supply all the world's fish suppers without using a drop of actual seawater? Dr Rebecca Gentry, a marine scientist at Florida State University, suggests we wouldn't need to. Theoretically, aquaculture in the sea could produce the equivalent of the world's fishing catch in less than 1 per cent of the ocean surface, her 2017 paper shows. “It's an interesting thought experiment,” she says. “If we close all wild fisheries, look at this huge amount of ocean area that we're no longer having an impact on.” She doesn't want to paint “too sunny a picture” of aquaculture, though, noting that any large-scale food production fundamentally changes the environment. ➤



3

Stocks would recover, but not all of them

Temporary bans on fishing of certain species are already used worldwide to maintain fish stocks and protect the environment. Some last a few weeks or months annually. These seasonal bans are designed to protect fish during their breeding seasons, for example, or to protect the sea bottom from damage, as with shrimp trawling bans. Others last most of the year, or longer, as in the current moratorium on fishing in the Arctic, which could last 16 years. A total global fishing ban would increase stocks, while helping to rebalance upset ecosystems. Eating less lobster thermidor, for example, would help keep seaweed forests in good health, as the crustaceans prey on sea urchins that destroy kelp – a type of seaweed.

However, there are no guarantees of a full recovery in

our oceans. According to Purcell, some species are already so badly affected by overfishing that they might never recover. In Papua New Guinea, the edible sea cucumbers that he studies – popular in Asian cookery – have been so voraciously harvested that their populations are down to one-hundredth of their pre-fishing levels. “Once they get down to less than one animal per hectare, it’s very hard for the mates to find each other, particularly for these species that aren’t moving very fast,” Purcell says. “They have to crawl around on the seafloor to find each other.” Meanwhile, north of Australia, some shellfish populations exploited by Indonesian fishers have declined to the point where so few are now reproducing that rebuilding their populations looks impossible.



4

The oceans would be cleaner

Recent years have seen single-use plastics demonised as the public has woken up to the effects of marine plastics. But few people realise the contribution that fishing makes. Lost fishing gear accounts for about 10 per cent of all marine litter and, according to a 2018 study, 86 per cent of the big pieces of plastic floating in the ‘Great Pacific Garbage Patch’. Without fishing, we’d also wipe out pollution and emissions from fishing boats (one 2014 study claimed that lobsters were the most fuel-intensive species, with some boats using 20,000 litres of fuel to catch a single tonne). However, aquaculture could bring other sources of pollution, such as feed and chemical products that are used to control disease. These pollutants enter the sea where fish are farmed in pens and cages. Franco says that aquaculture is, at least in some sectors, less polluting than it was. “Consider salmon farming in the UK – antibiotics have not been routinely used in years,” she says. “But regulations and conditions can be very different in different sectors and countries.” Nevertheless, aquaculture globally will have to become more sustainable if the farmers want to access the most valuable markets, as these demand higher standards.

A further concern is that pushing seafood production onshore into high-tech systems like recirculating tanks would take space from other food production industries. One space-saving solution could be an integrated, ‘multitrophic’ system, growing fish, bivalves like mussels, and seaweed altogether. Gentry reckons that anything involving seaweed is “fabulous”, as the plants extract pollutants from the water, helping to purify it.

5

Corals would get some respite



Fishing affects the whole ecosystem and, as such, reef fishing has had a huge impact on some of the most vulnerable marine ecosystems – corals. Banning fishing could not only relieve pressure on some of the 4,000 fish species that live around coral reefs, but also on the corals themselves.

It's not always immediately obvious how fishing affects the corals, but Purcell gives one example. Crown-of-thorns starfish are a scourge on reefs because they eat the living part of the corals – the polyps. If the starfish populations are not controlled by

predators, too many polyps will fall prey to these spiky creatures. But the starfish's predators are emperor fish, which are caught for food, and triton snails, which are prized for their shells. "I don't think [fishing] is the only reason we're getting outbreaks of crown-of-thorns starfish," says Purcell. "But it's one of the problems, and it contributes to taking out the [starfish's] predators."

Meanwhile, climate change and increasing sea temperatures continue to stress and bleach corals, which can then become overgrown with algae. A fishing ban could help bolster

populations of the fish needed to clean away this suffocating slime. Cleaning up coral reefs could also ensure that they remain tourism destinations for years to come, supplying local communities with precious income, especially if fishing wasn't an option. **SF**

by HAYLEY BENNETT
(@gingerbreadlady)
Hayley is a science writer and (sustainably sourced) fish finger sandwich fan, based in Bristol, UK.

COUNTING FISH

So-called 'environmental DNA' is helping conservationists keep track of marine species

by DR HELEN SCALES

As plenty of scuba divers will tell you, they rarely find themselves in exactly the right place at the right time to spot a whale shark, a basking shark, a hammerhead or any other shark species gracefully gliding by. Shark researchers face this same dilemma in their studies. They'll spend days and weeks at sea hoping for shark encounters. Conventional surveys involve scuba diving, setting fishing lines to catch sharks or lowering video cameras into the sea, along with chunks of bait that sharks might come up and chew. But now there's a much quicker and cheaper shark-tracking tool – a bucketful of seawater.

"The ocean is a soup of DNA," says Dr Judith Bakker, a postdoctoral researcher at Florida International University. "Everything from small plankton to gigantic whales are constantly leaving behind traces of DNA."

In the environment, you can find snippets of genetic material from mucus, skin cells, urine and faeces. Over the last 10 years, scientists have worked out how to gather these small DNA fragments – known as environmental DNA or eDNA – and convert them into a powerful tool to track species without actually seeing them.

In a study spanning the Pacific island of New Caledonia and various spots in the Caribbean, Bakker

screened water samples for shark eDNA. "A couple of years ago, people were very sceptical," she says. The eDNA technique was originally developed to study soil microbes, and was later used in streams and ponds to search for invasive species like American bullfrogs. It took a while to catch on with marine scientists, as they assumed there wouldn't be enough DNA to detect species swimming through these vast bodies of water. But Bakker and her colleagues took on the challenge and eventually fine-tuned the technique for detecting sharks.

"Many shark populations are overfished, they're threatened," says Bakker. The first step for effective conservation programmes, she explains, is knowing which species are present and eDNA could help do just that.

"In the Bahamas, where commercial shark fishing is banned, Bakker found eDNA from 11 species"

FIRST GET THE DNA

The technique Bakker uses is essentially the same for all aquatic eDNA studies. First, she motors out to each

sampling site at sea, scoops up a few litres of water and pours it through a fine filter to snag the DNA fragments from all the species that have recently swum by. Back in the lab, Bakker adds a primer that picks out all of the fragments of shark DNA. Primers are short DNA or RNA strands that act like highly specific strips of Velcro and stick only to particular DNA sequences, in this case only the codes specific ➤

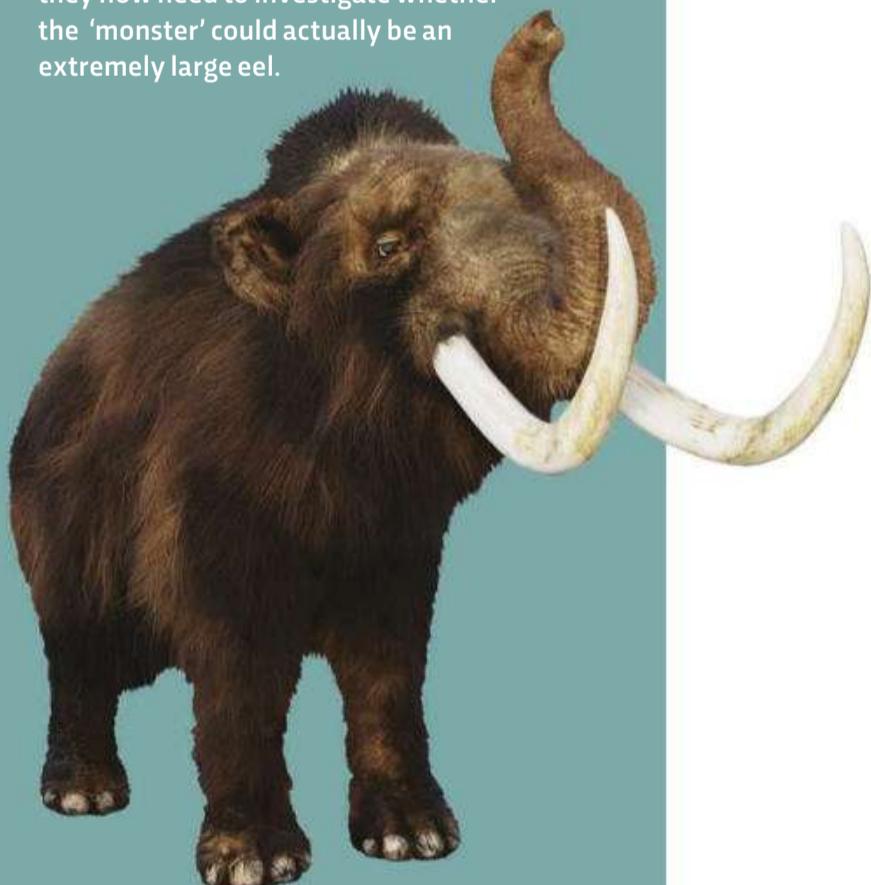


HUNTING FOR ANCIENT BEASTS

For land-based scientists, a handful of soil can tell them which animals have crawled through it or flapped their wings overhead. A chunk of permafrost can even reveal whether, thousands of years ago, a woolly mammoth trudged past. A study of eDNA in Alaska suggests that mammoths were still alive until 10,500 years ago, almost 2,000 years later than previous estimates based on mammoth bones. If this new extinction date is accurate, it means humans and mammoths co-existed for several millennia.

Insights into past climates and ecosystems also come from eDNA. Ice cores taken from Greenland contain traces of eDNA from conifer trees and insects, showing that the land now lying beneath two kilometres of ice sheet, was once a flourishing forest.

This cutting-edge technology also helped solve a centuries-old puzzle. An international group of scientists, calling themselves the Super Natural History team, probed Loch Ness in Scotland to find out once and for all if a monster really does lurk in the dark depths. The eDNA sequences they decoded found no evidence of plesiosaurs, sharks, sturgeon or catfish. They did, however, find a lot of eel DNA, so they now need to investigate whether the 'monster' could actually be an extremely large eel.



RIGHT Judith Bakker collecting samples of seawater for the eDNA material it contains

BELOW Remote control drones could be used to gather eDNA from the ocean depths

to sharks. Next, she makes multiple copies of the shark eDNA fragments and feeds them into a high throughput sequencing machine. After 24 hours or so, the machine produces huge data files with masses of DNA sequences, which she then compares with known DNA databases to work out which species the eDNA fragments came from.

Her studies have so far detected 21 shark species and shown that parts of the oceans protected from fishing have a greater shark diversity. In the Bahamas, where commercial shark fishing is banned, Bakker found eDNA from 11 species. In the less well protected waters of Jamaica and Belize, she only found a couple of different sharks.

A major benefit of eDNA is that it's not invasive – you don't have to catch and handle sharks, which can stress them out. Also, the technique avoids any bias caused by behavioural quirks of different species. "If you go fishing, you may catch five tiger sharks," says Bakker, "but perhaps you don't catch the bull sharks because they're just not attracted to your fishing line."

Another recent study in New Caledonia, led by Dr Germain Boussarie from the University of Montpellier, showed just how well eDNA outperforms other surveys. Water samples collected during two weeks of fieldwork provided DNA that identified more shark species than were detected in two years' worth of underwater baited camera studies and thousands of scuba dives. The eDNA samples found sharks 90 per cent of the time, compared to only

50 per cent in camera studies, and 15 per cent in dive surveys.

But still some sharks are missing. Working in the Caribbean, Bakker and her colleagues regularly saw nurse sharks but failed to find any traces of their eDNA. The problem comes down to the primers. "They just don't like to attach to nurse shark DNA," says Bakker. Fixing this primer mismatching is one of the improvements she hopes to see in eDNA techniques in the coming years.

There's a Goldilocks quality to DNA fragments in water: it doesn't vanish too quickly or linger too long to be useful. If the eDNA of a tiger shark is found, then one probably swam nearby in the last day or two. Any longer and DNA gets broken down by saltwater, UV light and bacteria until the fragments are too small to detect. Bakker is hopeful that advances in the technique will soon allow her not only to work out which sharks



GETTY IMAGES, JUDITH BAKKER, BRIDGES



ALIEN SPECIES SURVEILLANCE

Environmental DNA makes an ideal early warning system for alien invasive species – creatures that find themselves in places they aren't expected or wanted. Given half a chance, many successful invaders will rapidly multiply and unleash economic and environmental havoc, like zebra mussels that block intake pipes of water treatment plants and Chinese mitten crabs that crumble riverbanks with their burrows. DNA fragments can show when a potentially invasive species is present in small numbers and hasn't yet become a pest. The sooner an invasion is discovered, the more likely control measures are to work. From pondweed and clams, to fish and sponges, eDNA is used to monitor all sorts of invasive species. In the US, eDNA helps conservationists quickly find out if an invasive European pig has wallowed in a pond, or if it remains pig-free. With climate change, invasions are likely to become more problematic as temperatures rise and more species try to compensate by shifting their ranges. We're already seeing the spread of species into British waters, such as the carpet sea-squirt, a gloopy, fast-growing animal that smothers other life, including oysters and mussels in shellfish farms.

are there, but also how many of them. For now, eDNA can only give a rough guess at abundance. "We can say that most likely there's a lot more sharks in this area than that area," she says.

Off the coast of Greenland, a study has shown that eDNA could revolutionise the way fisheries are monitored. Researchers collected water samples and extracted eDNA from more than 30 fish families, including many that are important in commercial fisheries. The team found that the abundance of eDNA broadly matched the amount of fish they caught in conventional trawl surveys in the same area. The new technique could also help survey species that rarely show up in trawl nets. They found lots of eDNA from Greenland sharks, elusive giants that can live for 500 years. But the trawl surveys only caught one Greenland shark, suggesting that many others avoid the nets.

CALL IN THE DRONES

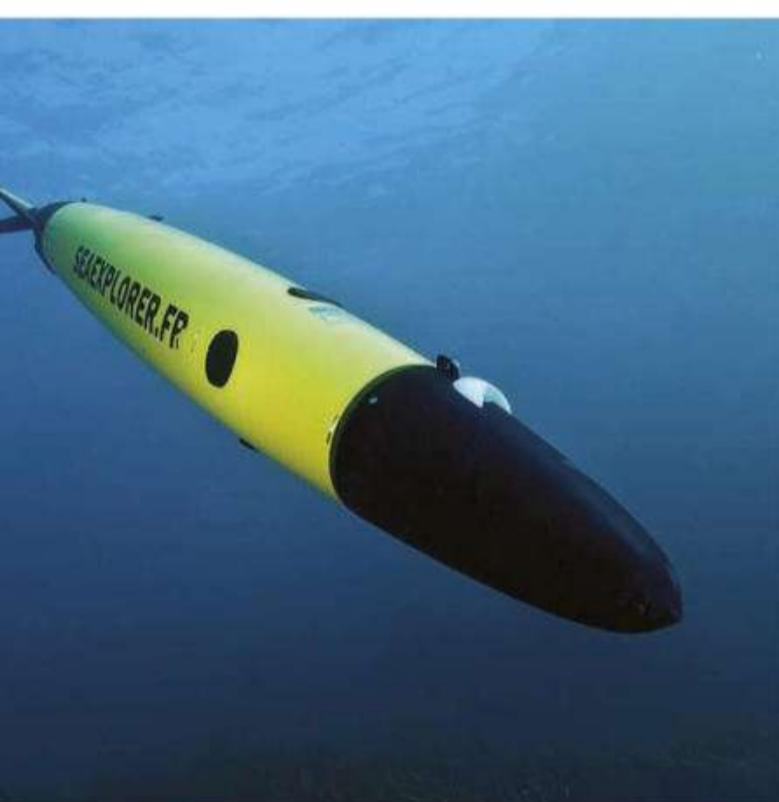
In the next few years, fisheries scientists could start to abandon trawl surveys and instead use eDNA to count fish. And to

collect water samples, scientists might even throw away their buckets and start sending out fleets of drones and underwater robots to get water for them. Already there are ocean gliders that look like a cross between miniature submarines and aeroplanes, fitted out with scientific sensors and instruments. They can be programmed to navigate on their own for thousands of kilometres through the seas, gathering measurements as they go, like salinity and temperature. Equipped with water-sampling devices, these robots could become the research tool of choice for eDNA studies, opening up remote stretches of the oceans that are otherwise difficult and expensive for scientists to get to, including down in the deep sea, many kilometres beneath the waves. **SF**

by DR HELEN SCALES

(@helenscales)

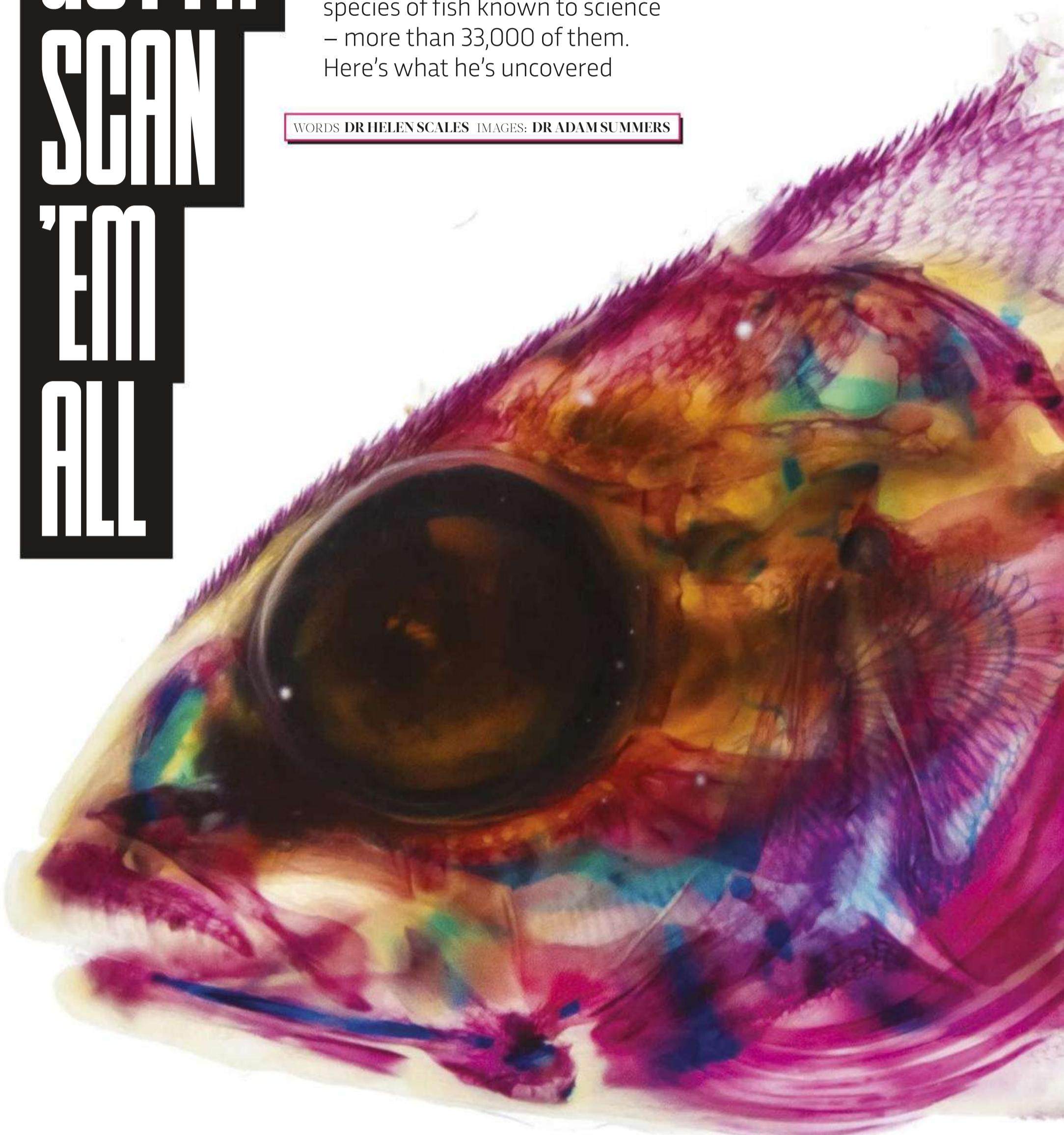
Helen is a marine biologist, broadcaster and author. Her next book, *The Sea Beneath Us* (£16.99, Bloomsbury Sigma), will be out in February 2021.



GOTTA SCAN 'EM ALL

An American researcher has embarked on a project to scan the inner structures of every species of fish known to science – more than 33,000 of them. Here's what he's uncovered

WORDS DR HELEN SCALES IMAGES: DR ADAM SUMMERS





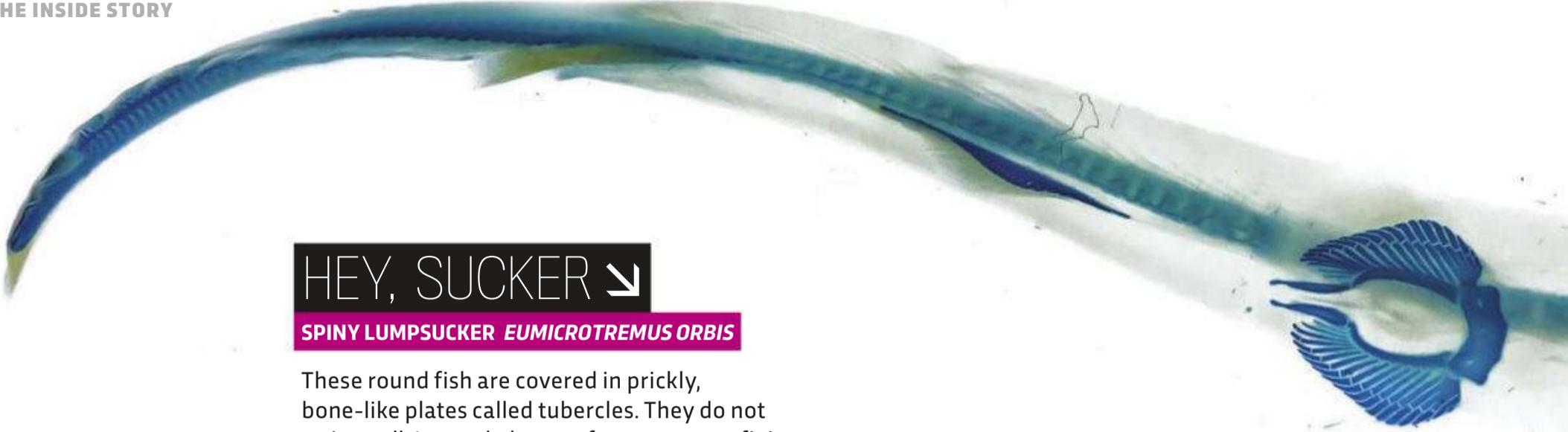
There is a small lab on Friday Harbor, San Juan Island, just off the US state of Washington. Here, marine biologist Dr Adam Summers spends much of his time painstakingly loading fish after fish into a CT scanner to produce detailed images that reveal their intricate skeletons and inner structures. The project began inauspiciously several years ago when Summers would pay covert night-time visits to local hospitals, begging to use their CT scanners during periods of downtime. "We would stuff dead sharks and rays and things into bags, so nobody could tell what they were," he says.

After amassing a library of several successful scans, he began sharing his results on Twitter. To his surprise he got a huge response, with many biologists asking him to scan their favourite fish. "I jokingly replied that I was going to #ScanAllFish," he says. At the time, he didn't really believe that would happen because it was taking 12 hours to scan three or four fish, and there are over 33,000 species to get through. But with more than 4,600 species scanned so far, he reckons the project could be completed in as little as two years, though they may have to skip some of the biggest, rarest fish.

Thanks to the success of his images, Summers applied for a grant for his own CT scanner, which has been installed in his labs. Every scan is immediately posted online for anyone to use, with Summers not asking for any credit. The project has already racked up more than half a million downloads, with everyone from scientists and engineers to artists and teachers using the images. "We're exposing our data to a world of people who have great brains and will do far better things with it than we ever could," he says.

Anyone can use the scanner to scan their favourite species, provided they make the data freely available. "If you come to the island you can bring a suitcase full of dead things and CT them," says Summers. He is also collaborating with museums worldwide to scan their collections. It is hoped that these 'digital dissections' will allow people to see inside fish and manipulate them in ways that is just not possible with preserved specimens.

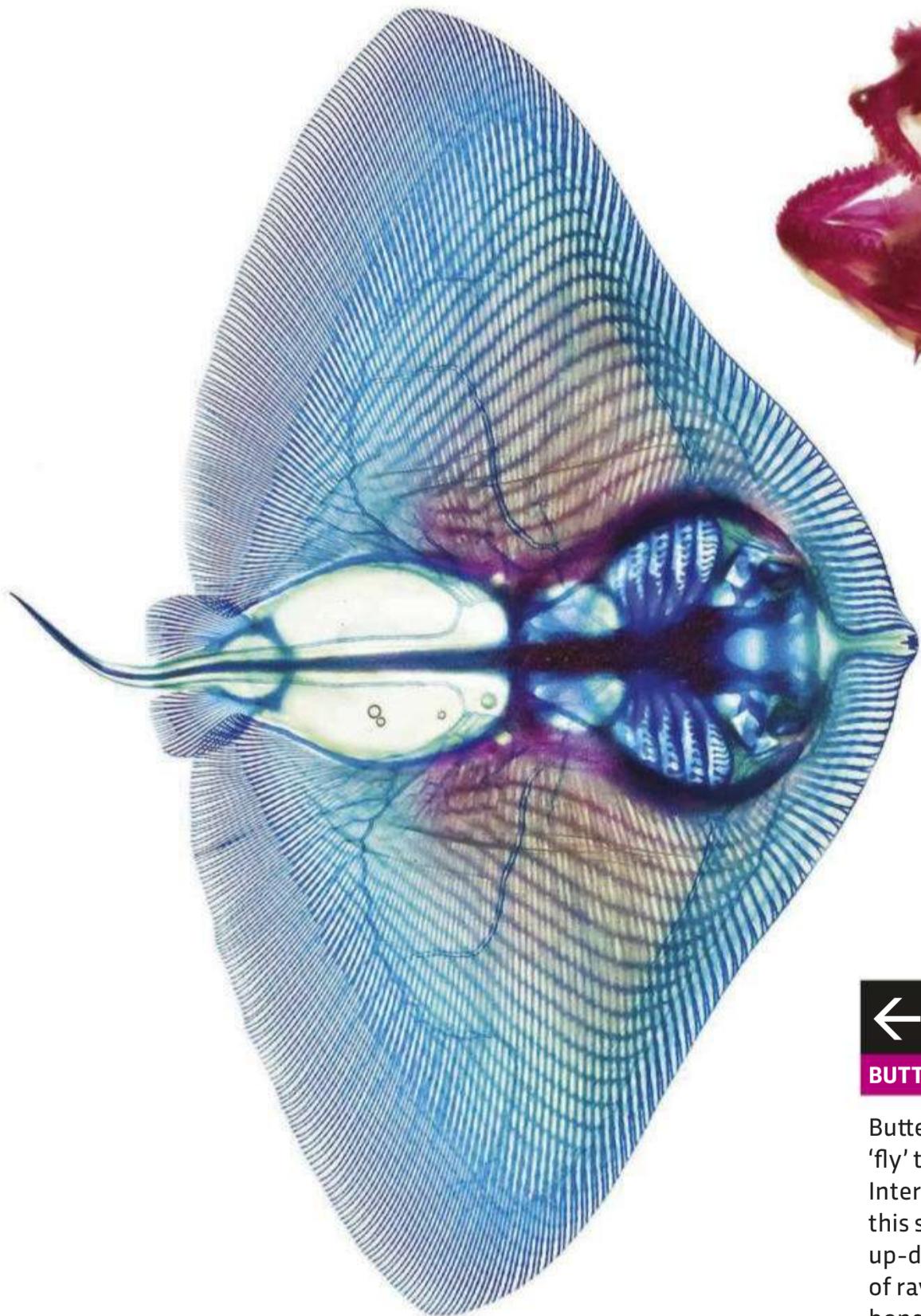
As well as CT scans, Summers also makes fish skeletons visible through their skin using dyes that stain bone red and cartilage blue. He bleaches the fish white with hydrogen peroxide and dissolves its flesh with the digestive enzyme, trypsin, leaving only skin and connective tissue. The fish is then photographed while immersed in glycerine, which renders the unstained parts invisible. ➤



HEY, SUCKER ↴

SPINY LUMPSUCKER *EUMICROTREMUS ORBIS*

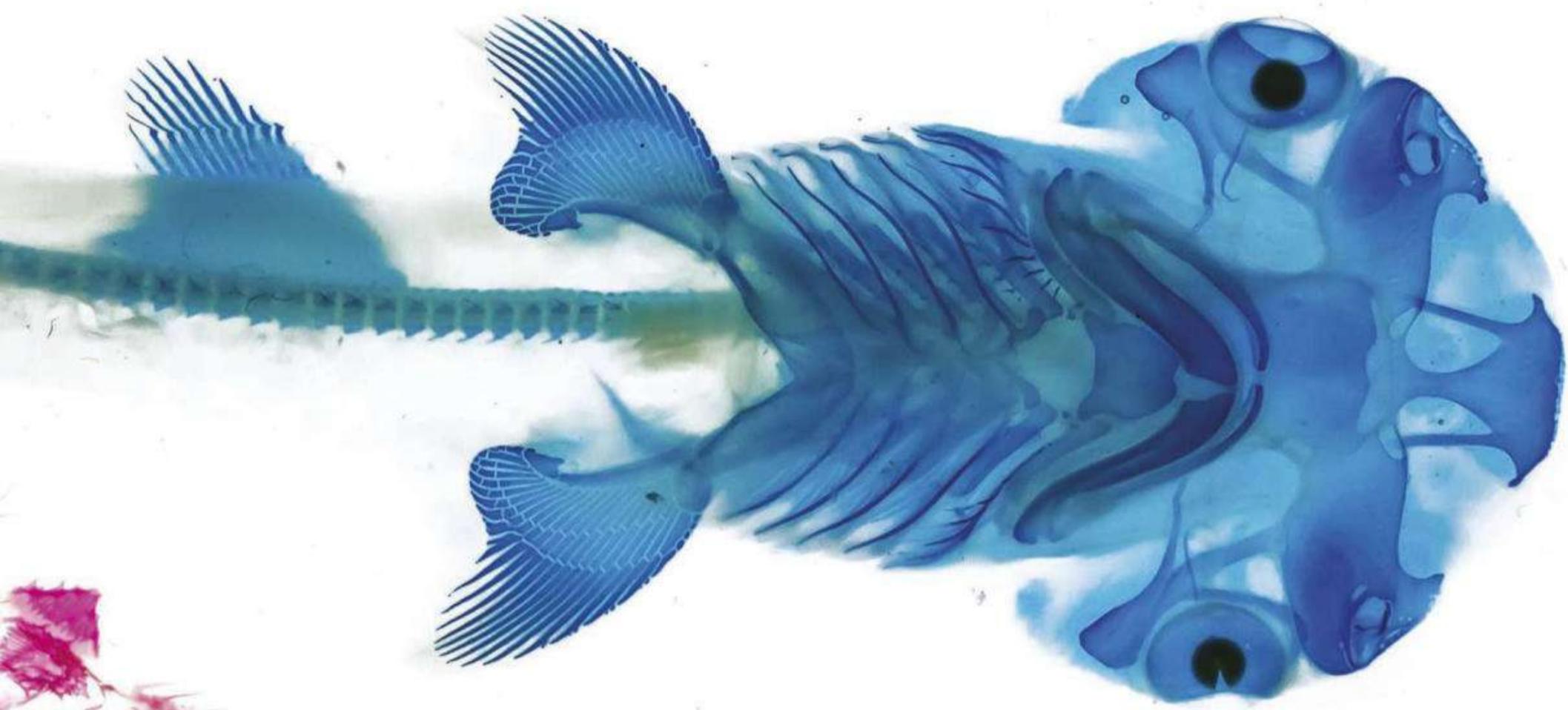
These round fish are covered in prickly, bone-like plates called tubercles. They do not swim well. Instead, they prefer to stay put, fixing themselves to rocks, seagrass and kelp. They can do this because their pelvic fins have evolved into a suction cup that's a lot like the ones that are used to stick sat-navs to car windscreens.



← BLUE RAY

BUTTERFLY RAY *GYMNURA* SPECIES

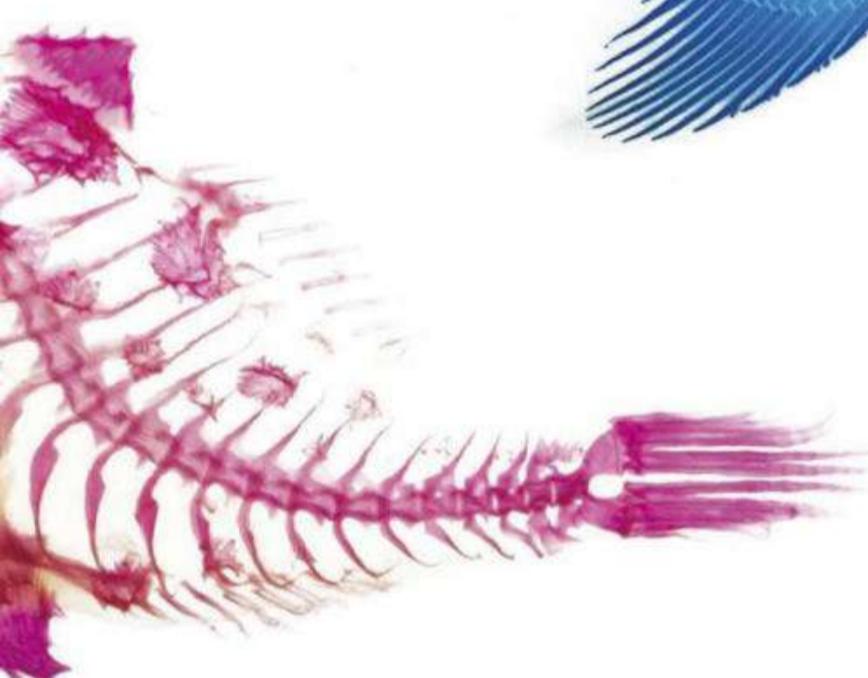
Butterfly rays are found in warm oceans and appear to 'fly' through the water by moving their fins up and down. Interconnected segments of the fine fin rays, visible in this stained image, could be the key to translating that up-down motion into underwater flight. As the skeletons of rays, skates and sharks are made of cartilage and not bone, they stain blue rather than red.



↑ NIFTY
MOVER

BONNETHEAD SHARK
SPHYRNA TIBURO

While chasing prey, bonnethead sharks turn incredibly sharply. Scientists originally thought their odd-shaped heads might help their acrobatics, but their heads stay flat as they turn – so probably not. Summers' bonnethead scan revealed their secret. Most sharks are circular in cross-section behind their heads. The bonnethead's body is shaped like a pumpkin seed, making it super aerodynamic. "That means they can turn really well," says Summers.



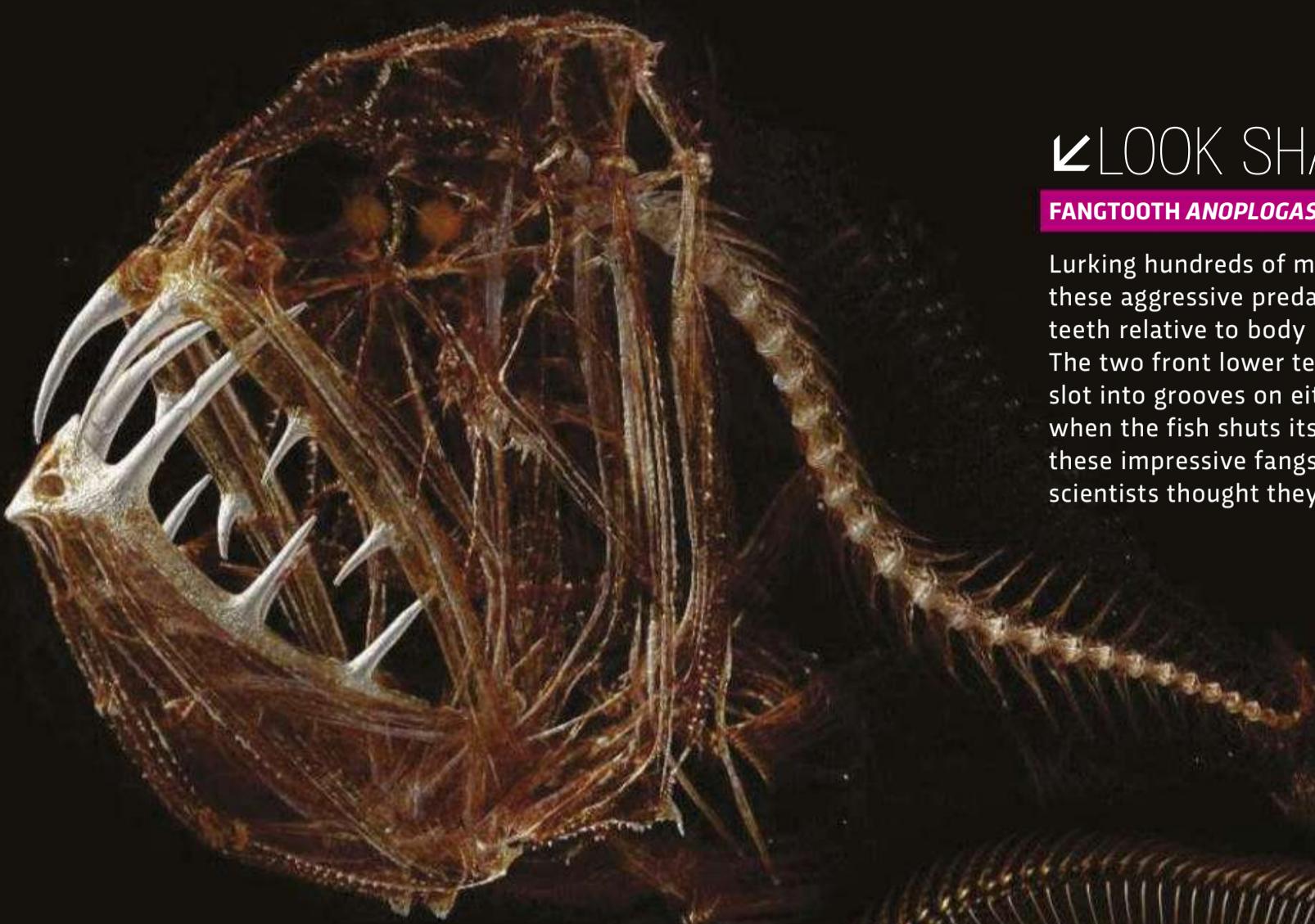
↑ DADDY
DAY CARE

TUBE-SNOUT

AULORHYNCHUS FLAVIDUS

Relatives of seahorses, tube-snouts are the size of pencils and often swim together in large schools. The females are drab and well-camouflaged, while the males have shining patches on their snouts and bright red fins. Females lay eggs on kelp, sticking them in place with goo secreted by their kidneys. Males then guard the nests against predators.





↙LOOK SHARP

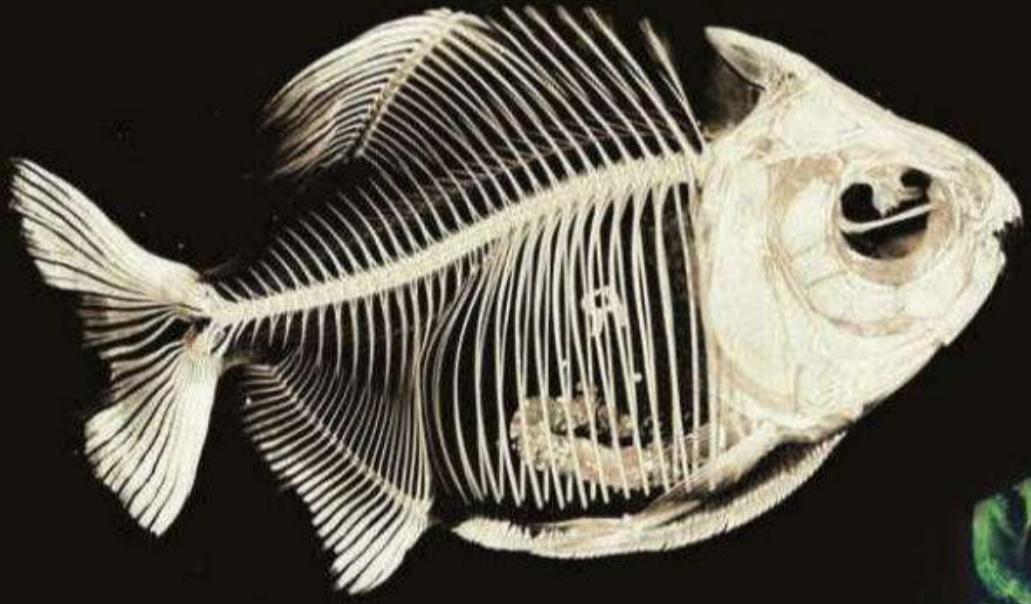
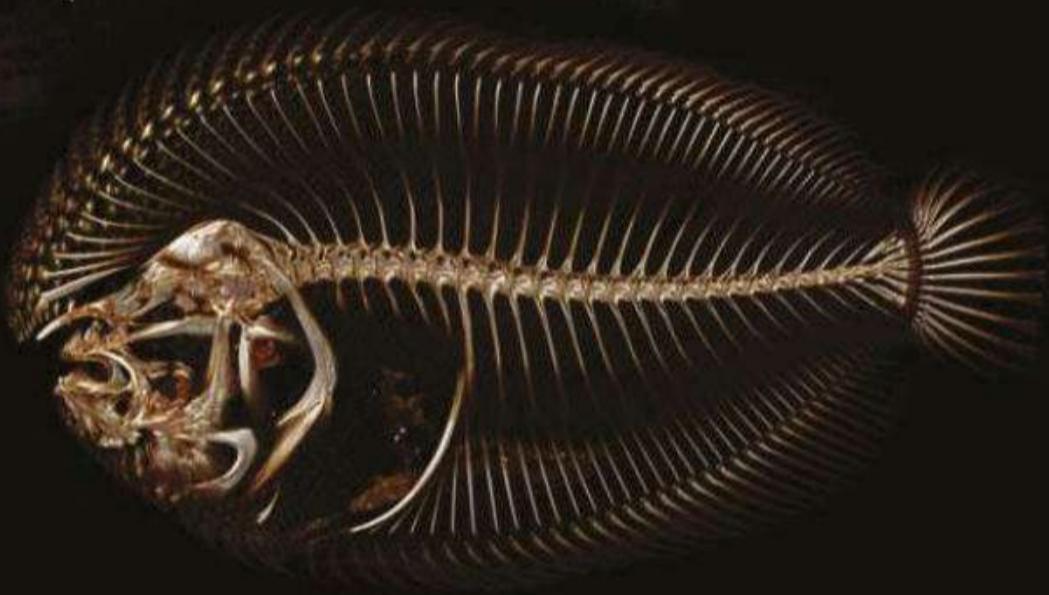
FANGTOOTH *ANOPLOGASTER CORNUTA*

Lurking hundreds of metres beneath the waves, these aggressive predators have the largest teeth relative to body length of any sea creature. The two front lower teeth are so long that they slot into grooves on either side of the brain when the fish shuts its mouth. Juveniles lack these impressive fangs and for over a century, scientists thought they were a separate species.

NUTTY GNASHERS↓

PIRAPITINGA *PIARACTUS BRACHYPOMUS*

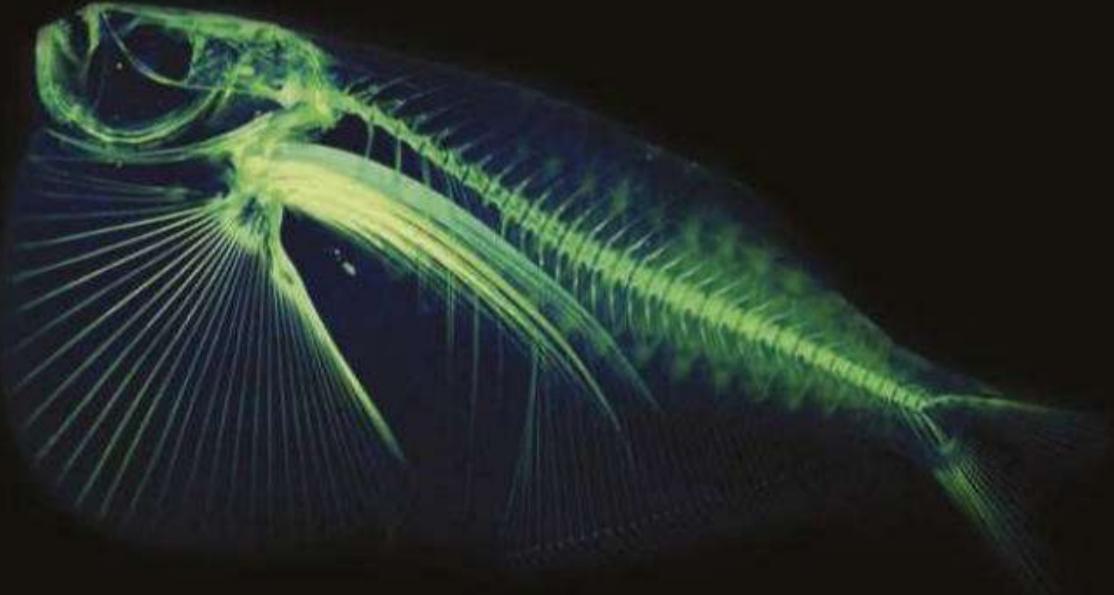
The chomping teeth of these fish make them look like they stole a set of human dentures. Though related to piranhas, pirapitinga are harmless herbivores that chew on seeds and nuts. They belong to a group of fish called the serrasalmids, which are well ahead in the race to #ScanAllFish, with 86 out of 90 species already in the database.



CATCH A BUZZ→

SPOTFIN HATCHETFISH *THORACOCHARAX STILETTOS*

Hatchetfish frequently leap from the water. The buzzing sound they make while flying through the air led people to believe they flap their fins as wings. In fact, they glide, holding their fins still. A quarter of their body mass is made up of huge pectoral muscles, giving them pre-flight propulsion. The deep belly adds stability during take-off and landing.



↑BOSS EYES!

HOGCHOKER *TRINECTES MACULATUS*

Like all flatfish, hogchokers begin life as larvae with a normal, upright stance and one eye on each side of the body. Then comes a point when one of their eyes gradually slides over the head to join the other. It can be either eye that moves, but in the case of the hogchoker it's the left.

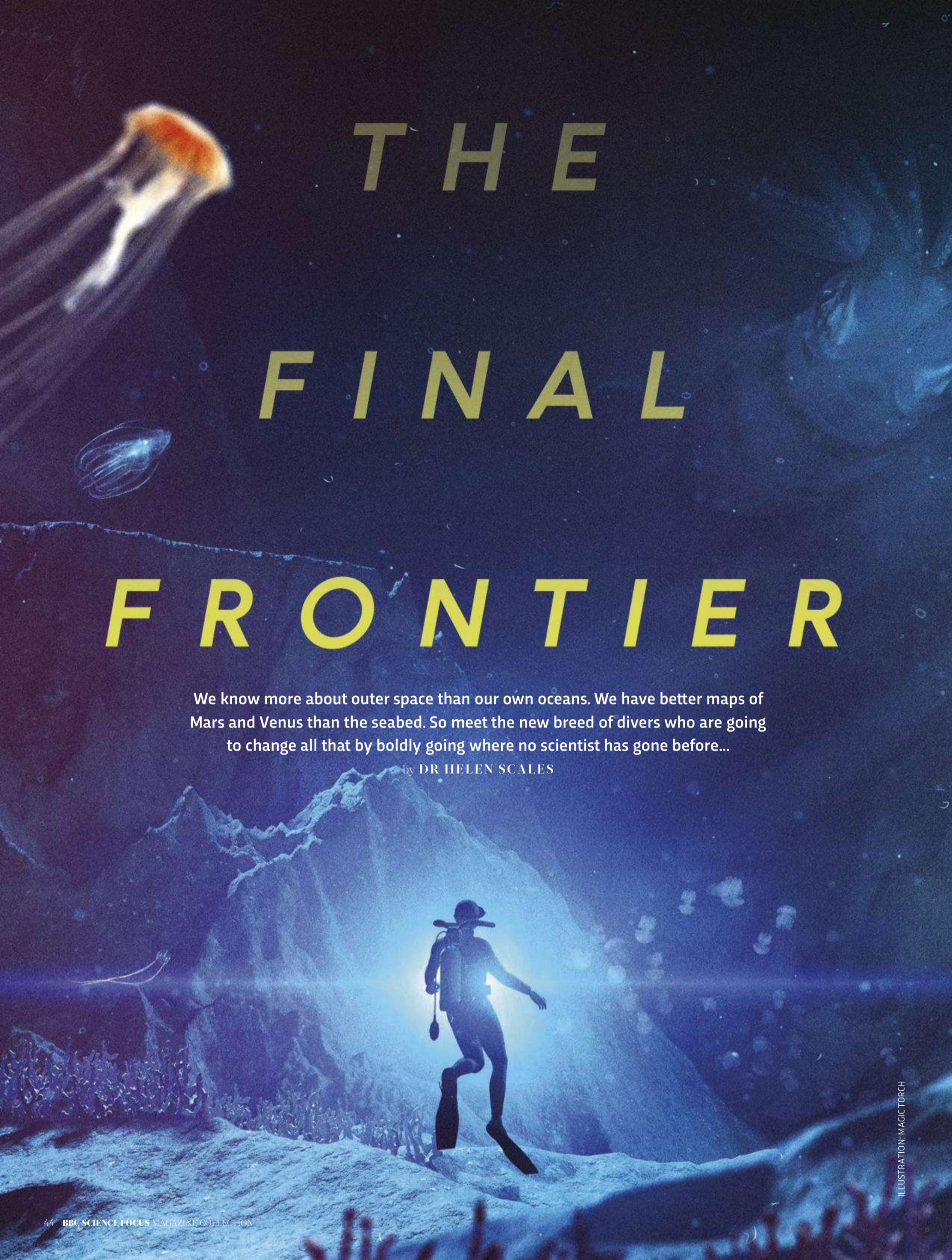


BEAUTIFUL ON THE INSIDE →

SCALYHEAD SCULPIN *ARTEDIUS HARRINGTONI*

Scalyhead sculpins live in coastal regions of the western US and British Columbia. Despite being just 10 centimetres long, the males are highly territorial and will guard their mate's eggs until they hatch out.

by DR HELEN SCALES (@helenscales)
Helen is a marine biologist, broadcaster and author.
Her next book, *The Sea Beneath Us* (£16.99, Bloomsbury Sigma), will be out in February 2021.



THE FINAL FRONTIER

We know more about outer space than our own oceans. We have better maps of Mars and Venus than the seabed. So meet the new breed of divers who are going to change all that by boldly going where no scientist has gone before...

by DR HELEN SCALES



Until about a century ago, it was thought that not much lived in the deep sea. With its average depth of around 3.5km, crushing

pressures and permanent darkness, few people bothered looking there – what could hope to survive in such an environment?

According to the US National Oceanic and Atmospheric Administration (NOAA), more than 80 per cent of the oceans are still completely unexplored. But today's scientists have ditched the old ideas of a deep, empty ocean and flat, featureless seabed. They're keen to take a closer look beneath the waves, and the latest generation of research equipment is opening up the depths like never before. New technology is helping scientists uncover the oceans' vital role in global climate, and find bizarre creatures that offer clues about the origins of life on Earth – and the possibility of life in outer space.

"It feels like I'm somewhere I shouldn't be. This kind of exploration can give you tingles"



DEEPER DIVING

Exploring the mysterious 'twilight zone'

"It feels like I'm somewhere I shouldn't be," says marine biologist Dr Jack Laverick, as he recalls being the first person to see part of a 100m-deep Caribbean reef. "This kind of exploration can give you tingles."

He's one of a new breed of scientists who are venturing deeper than most scuba divers ever go. Divers can now descend into the 'twilight zone', from 50m down, where sunlight begins to run out. Few have visited these depths, but now rebreathers are making it possible.

Although invented before scuba equipment, rebreathers have only recently become safe enough for use in research. Instead of bubbling exhaled air into the water they recycle it, scrubbing out carbon dioxide and

topping up the breathable oxygen. Astronauts on space walks use similar apparatus while a team monitors them.

Dr Dominic Andradi-Brown, another deep-diving marine scientist, recounts the excitement of descending the sheer face of an underwater cliff. "It feels like you're going off the edge of an abyss and anything could be below you."

Laverick and Andradi-Brown took part in Thinking Deep, a 2015 dive off the island of Utila in Honduras. Using rebreathers, they dived into the twilight zone for up to four hours at a time. This let them access parts of the oceans that were understudied. Submersibles go much deeper than this, while regular scuba divers can't safely go beyond 40m. "There's this really understudied



middle bit," explains Laverick.

Less than a decade ago, researchers confirmed that tropical coral reefs grow into the twilight zone, despite corals usually being associated with the sunny conditions in shallow waters. These 'mesophotic reefs' could provide species with a refuge from threats that impact shallower waters, such as overfishing and rising sea temperatures. Laverick's research indicates that protected deep reefs may aid the recovery of shallow, damaged reefs.

Andradi-Brown, meanwhile, is studying fish. Below 60m, he's seen shark species that have been all but wiped out by fishing closer to the surface. "Coral reefs are a doom and gloom story at the moment," he says, "but these deep refuges are showing real potential."

CALL IN THE SEALS

How sensor-equipped seals have helped scientists peer below the Antarctic ice

Tagging huge elephant seals on an Antarctic beach isn't a job for the faint-hearted. Mature males weigh up to four tonnes, and can easily mistake a human for another seal looking for a fight. "Elephant seals don't have good vision," says Dr Horst Bornemann, a researcher from Germany's Alfred Wegener Institute for Polar and Marine Research. "You want a team who can anticipate their behaviour and fend off advancing territorial males."

There's a good reason for working with such colossal, bad-tempered animals in remote, sub-zero conditions, though. Southern elephant seals, the deepest-diving seal species, can dive below 2,000m for hours at a time, so fixing small, electronic sensors to their heads can transform them into a fleet of researchers. These sensors gather data on the seals' movements – how deep they dive, what they eat and where they go – and can ping information back up to 250 times a day, when the seal surfaces for air.

Tagged seals can help answer important questions about the oceans. Over seven years, close to 20,000 dives were logged by dozens of elephant and crabeater seals in parts of the Bellingshausen Sea, off the Antarctic Peninsula, where research vessels rarely venture. Another study used information from a programme called MEOP – Marine Mammals Exploring the Oceans Pole-to-Pole – to understand more about why the West Antarctic ice shelves are melting, showing that a layer of warm, salty water is edging up to the continental shelves surrounding Antarctica.

"There are ice-covered areas, in which it's a huge effort to manoeuvre a ship," says Bornemann. "But seals can cope with any icy conditions, all year round. So you get perfect winter data." ➤



Attaching sensors to four-tonne elephant seals can be dangerous



ROBOT SUBS

How gliders are going where humans can't

“Very small, gentle submarines.” That’s how Dr Pierre Testor, an oceanographer and senior researcher at Centre National de la Recherche Scientifique (CNRS), describes the underwater robots he works with. In the 1980s, scientists came up with the idea of long-range vehicles that could explore hard-to-reach areas of the oceans. Today, fleets of autonomous robots, known as gliders, scour the seas for months at a time, gathering crucial data about how the oceans work.

When Testor starting carrying out his glider studies more than a decade ago, the worry of not knowing if costly equipment would make it back in one piece was tempered by the excitement of new discoveries. “I felt I was starting to do oceanography in a different way,” he recalls. Since then he’s seen gliders used in all spheres of ocean science, from physics to biology.

Current gliders can reach depths of 1,500m, but Testor is deputy science

coordinator of a European project, BRIDGES, which is developing new gliders that go much deeper. “We plan to produce a glider that’s able to go to really great depths, around 6,000m,” he says. This means they’ll be able to reach around 98 per cent of the oceans. A big part of the gliders’ success is their extreme efficiency: they consume about the same amount of power as two Christmas tree lights.

The new BRIDGES gliders are intended for academic and industrial uses, including monitoring pollution from deep-sea mines. Rare earth minerals are in huge demand from the electronics industry and could soon be extracted from the seabed and oceanic hydrothermal vents. Conservationists are concerned that such mines will be difficult to monitor, so it’s hoped gliders will help keep an eye on operations. Equipped with acoustic sensors, they’ll be able to detect clouds of metal-rich sediments churned up by the mines.

BELOW A depth chart of part of the Gulf of Lyon in the Mediterranean, produced using one of BRIDGES’ gliders

THE MOST MYSTERIOUS PLACES IN THE OCEANS

THE CASCADIA MARGIN

The Ocean Exploration Trust has found hundreds of spots off the US west coast, where methane bubbles out of the seabed like champagne, and where several little-known species are thriving.



GREENLAND

In 2012, researchers stumbled across a coral reef while taking water samples 900m down off Greenland's southern coast. Little is known about it, but similar reefs in Norway are 8,000 years old.



SILFRA FISSURE

In the middle of Iceland, this is the only place where you can swim in the crack between two continents (the Eurasian and North American plates). It gets 2cm wider every year.



BRIDGES X2, GETTY X2, ALAMY, NASA, BEDFORD INSTITUTE OF OCEANOGRAPHY

YUCATÁN PENINSULA

Thousands of deep sinkholes form part of the longest underwater cave system in the world. The caves are flooded with freshwater overlying saltwater, and many remain unexplored.



THE CHAGOS ISLANDS

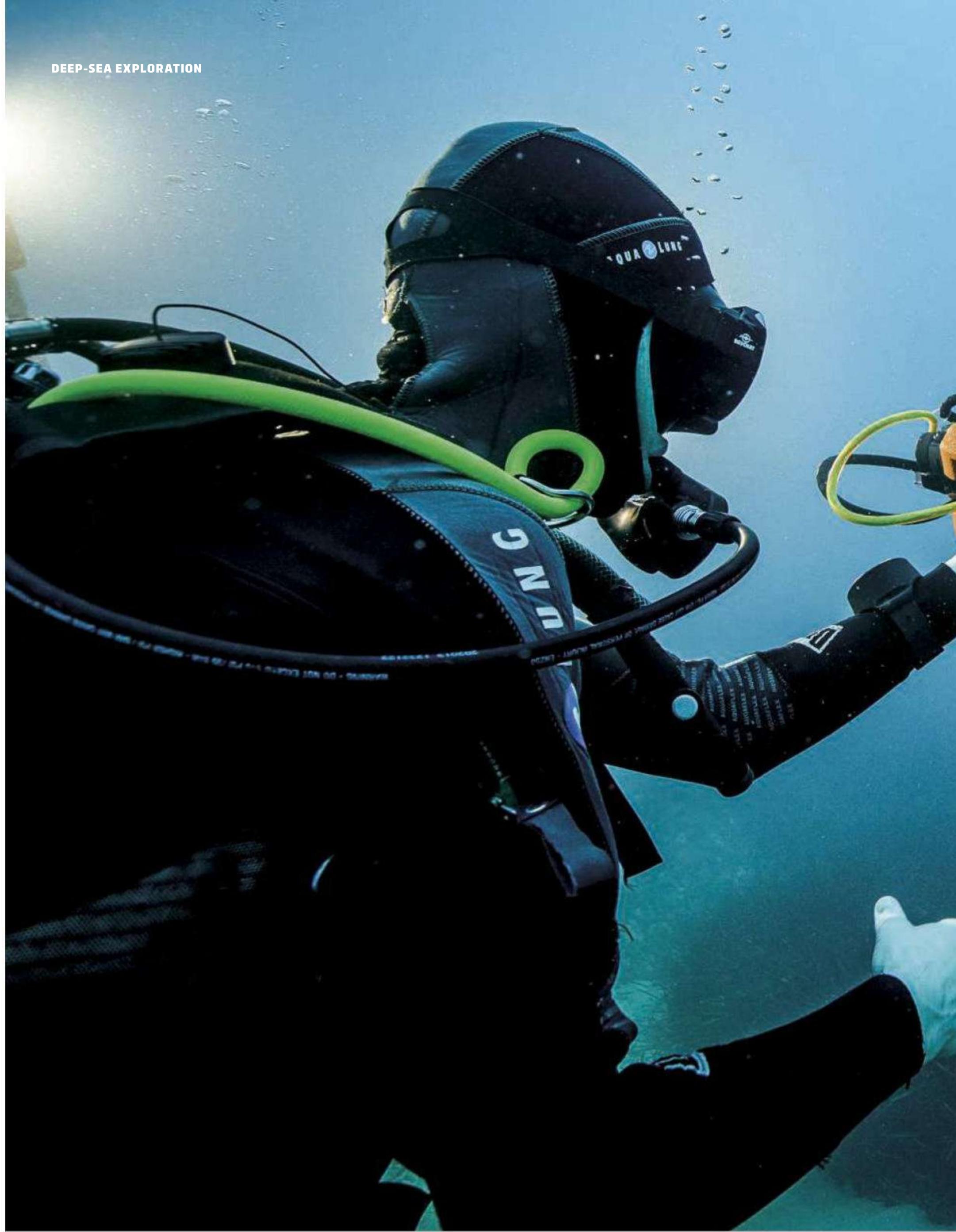
Few coral reefs have been studied deeper than 40m, but in the Indian Ocean, healthy deep reefs in the Chagos Islands could help shallower areas recover from mass coral bleaching.



THE ROSS ICE SHELF

Researchers drilling hundreds of metres through the world's largest ice shelf have found fish and crustacean species living underneath. How they got there – and survive – is a mystery.







LITTLE MERMAID

Building a distinctly human-like underwater avatar

Measuring 1.5m in length and weighing 180kg, OceanOne is quite unusual for a remotely operated underwater vehicle. Described as a 'robo-mermaid', it has a head, two cameras for eyes and a pair of fully articulated arms, complete with wrists and fingers. OceanOne acts as an underwater avatar, allowing people to feel like they're diving to inaccessible depths while remaining safe and dry. A human pilot can see what the robot sees via stereoscopic cameras, and feel what it's holding via sensors in the robot's hands that transmit haptic feedback to a controller on the surface.

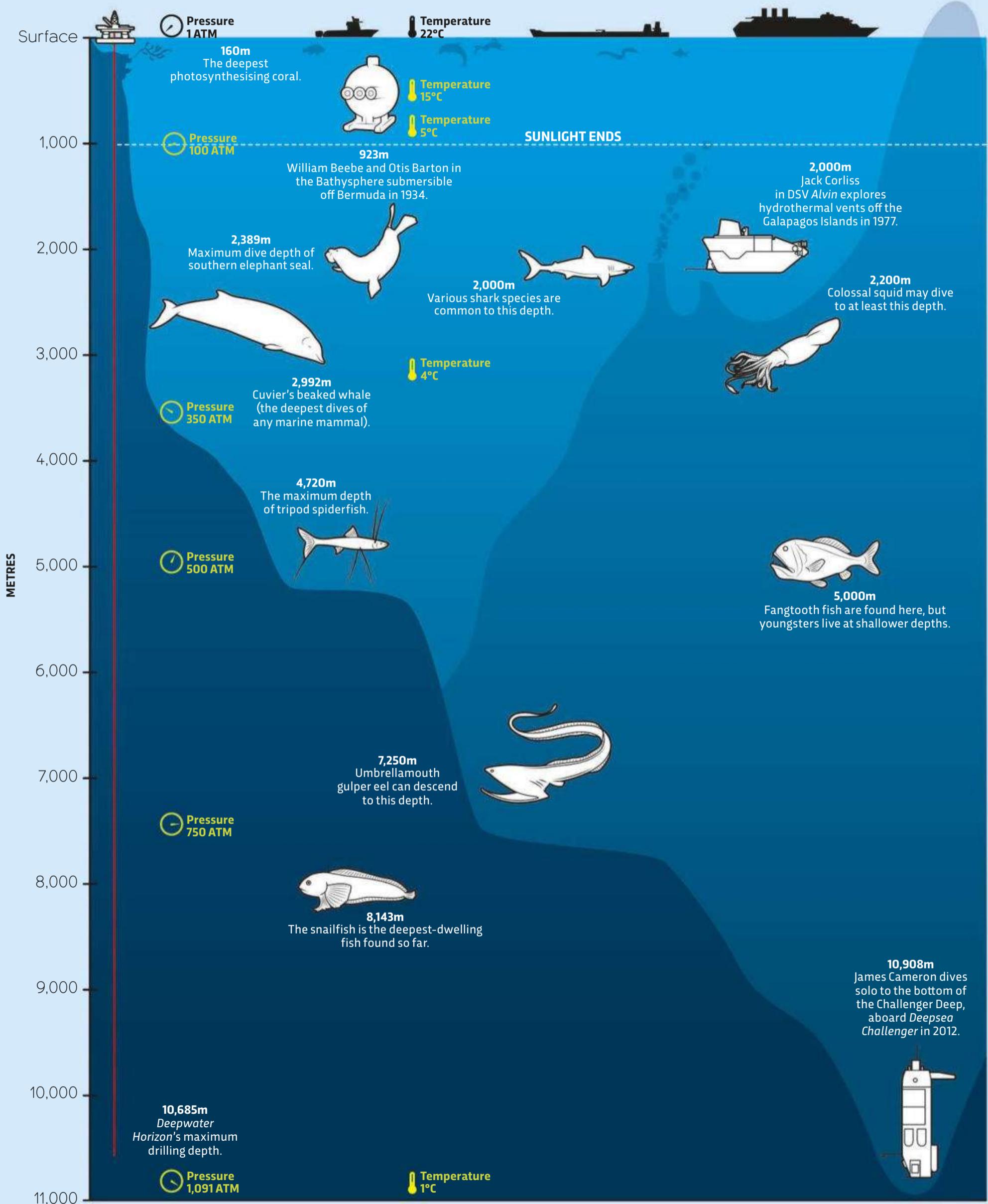
To a certain extent, OceanOne can even think for itself. Onboard processors analyse camera footage and adjust the thrusters in the

robot's tail to make sure it doesn't bump into anything. If sensors detect an unavoidable upcoming collision, the robot braces its arms to cushion the impact.

Built by a team at Stanford University, OceanOne's maiden voyage, in April 2016, was to explore the 17th-Century shipwreck, *La Lune*, lying 100m deep in the Mediterranean. The humanoid robot carefully swam around King Louis XIV's flagship vessel, gathering ancient artefacts without crushing them between its fingers.

The idea is that eventually, the robo-mermaid will be able to perform other skilled tasks, such as examining fragile coral on reefs or operating machinery in places such as deep-sea mines and oil rigs. ➤

WHAT LIES BENEATH



GOING DOWN, DOWN, DOWN...

How next-generation submersibles are enabling scientists to dive deeper than ever before

“It’s as close to being in space as you can be on the Earth,” says Oxford University’s Prof Alex Rogers, as he recalls his journey down to 3,380m inside the Japanese submersible Shinkai 6500. “You are so remote from your normal environment. There’s a real sense of isolation.”

Deep-ocean research initiative, Nekton, aims to accelerate the scientific exploration and protection of the ocean. On the first Nekton expedition in 2016, Rogers explored the deep sea around Bermuda inside a Triton submersible. This two-person, three-tonne sub is relatively small and lightweight compared to many other submersibles, and highly manoeuvrable. It also has a huge acrylic dome, giving scientists fantastic views of the ocean for observation and research. “The submersibles are absolutely fantastic. It’s very James Bond,” says Rogers.

Among the things that Rogers and the Nekton team observed were huge forests of tree-like black corals stretching down to at least 300m. Giant sea fans and enormous sponges add to the strange, living seascape. To reach deeper, the team will send down remotely operated vehicles and

other deep water probes.

The long-term aim for Nekton is to document the life at depths between 200m and 3,000m in 14 distinct regions worldwide. These 14 regions are defined by particular attributes of the oceans, including temperature, salinity and currents. The team will also measure the health of these deep ecosystems and look for signs of human impacts, like trawling and plastic waste. Who knows what else could be lurking in the deep?

Nekton uses two Triton submersibles, which gave Rogers a new perspective on the scale of the oceans. “You look across and see the other sub in the distance as this tiny, toy-like thing,” he says. “There are many scenes that are lodged in my memory. These majestic cliffs and landscapes... it can make you feel quite small.” **SF**



by **DR HELEN SCALES**
(@helenscales)

Helen is a marine biologist, broadcaster and author. Her next book, The Sea Beneath Us (£16.99, Bloomsbury Sigma), will be out February 2021.

DISCOVER MORE



Watch clips from iconic BBC One series The Blue Planet bit.ly/blue_planet_clips



ALIENS OF THE DEEP

While the ocean remains largely unexplored, we occasionally get a glimpse of the weird and wonderful creatures that eke out a living in the deep. Here are some that are totally out-of-this-world

WORDS: DR JON COPLEY

PHOTOS: SOLVIN ZANKL/NATUREPL.COM

FANGS A LOT

← FANGTOOTH

Two hundred metres is all that separates you from an alien world, right here on Earth. Descend that far into the ocean, and you enter the 'twilight zone' of the deep sea, where the Sun's rays gradually fade away and animals play a deadly game of hide-and-seek with predators in the shadows. Dive down beyond 1,000 metres and you're in the 'midnight zone', a vast darkness punctuated by flashes of light from life forms that hunt for food and seek mates here. It's a world with terrifying teeth, like those of the fangtooth fish. But don't let the fangtooth scare you: it's about the size of a grapefruit.

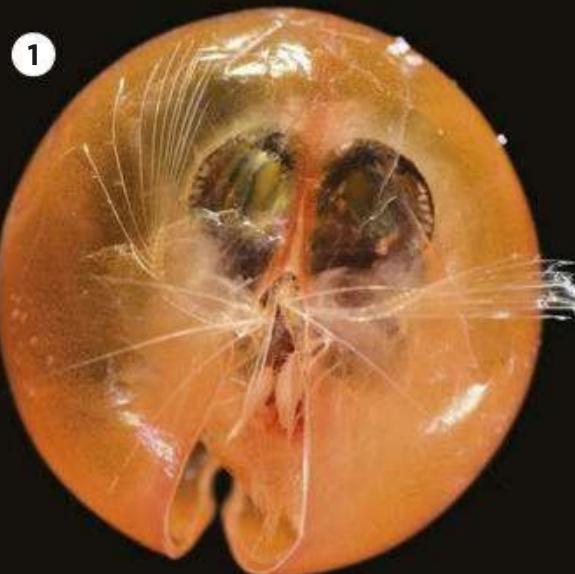
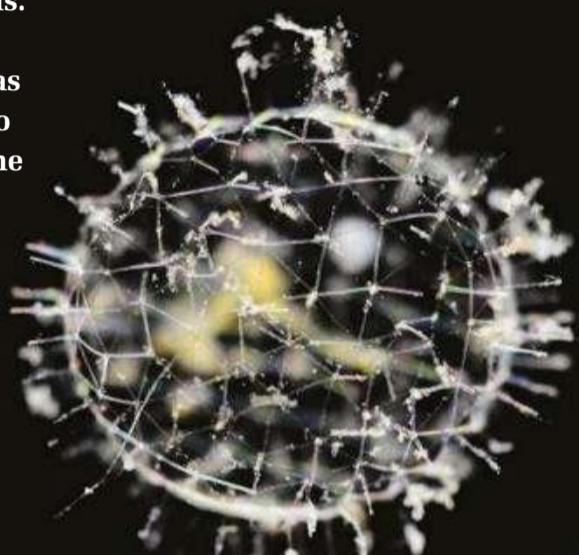


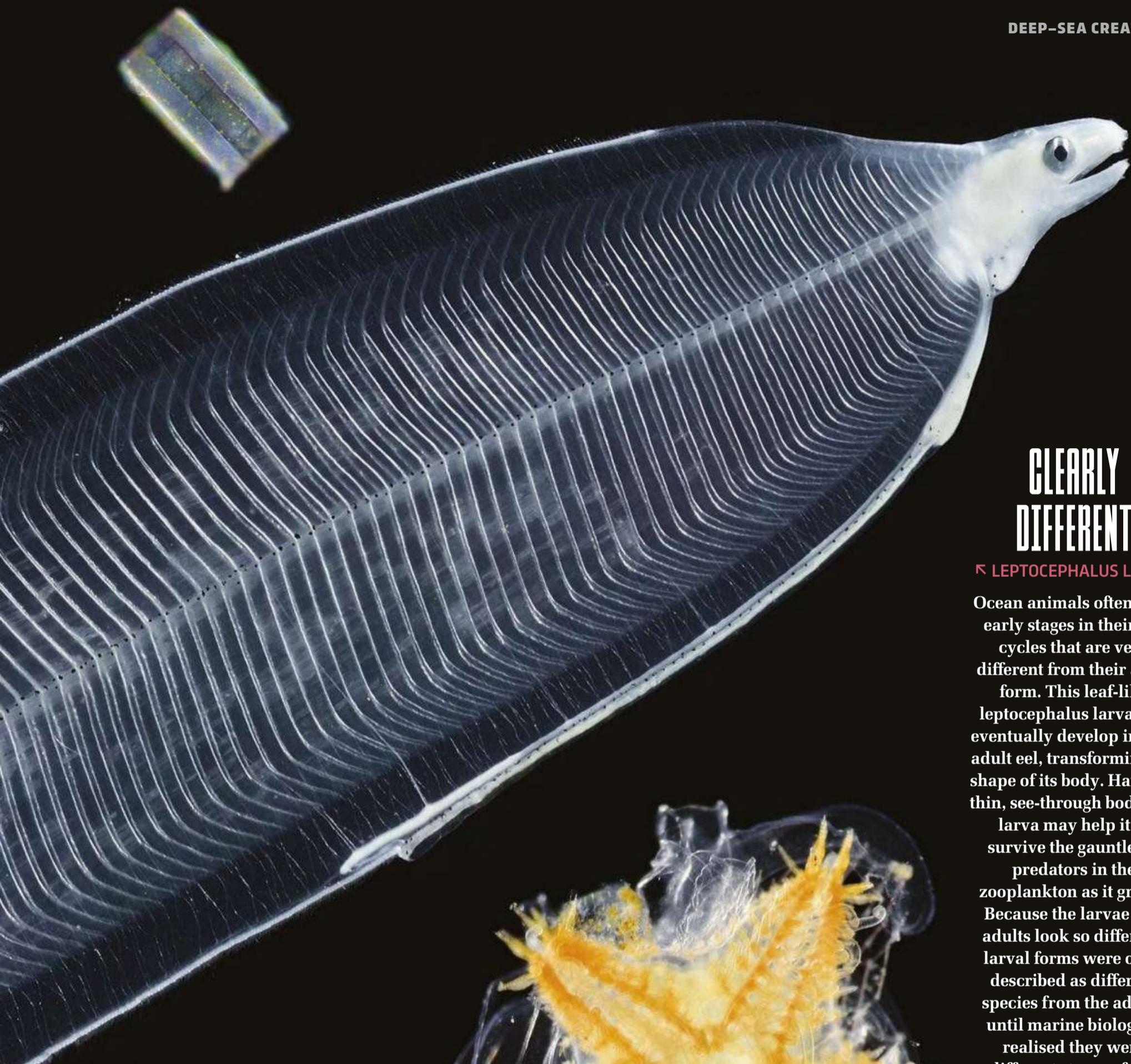
MICROSCOPIC MARVEL

ZOOPLANKTON (RIGHT & BELOW RIGHT) →

Lots of different animals drift in the 'inner space' of the deep ocean, where they are collectively known as zooplankton – from the Greek for 'animal drifters'. Some of them live their whole lives as drifters, such as the 'seed shrimp' (1) tucked up in its orange carapace, and the 'sea butterfly' (2) – a snail that swims instead of crawls.

Others are only temporary members of the zooplankton – the larval stages of animals such as seastars (3), which eventually sink back down to continue their lives on the seafloor. Spending time as drifters means they can be carried to new places by ocean currents, if they're not eaten by other zooplankton on the way.

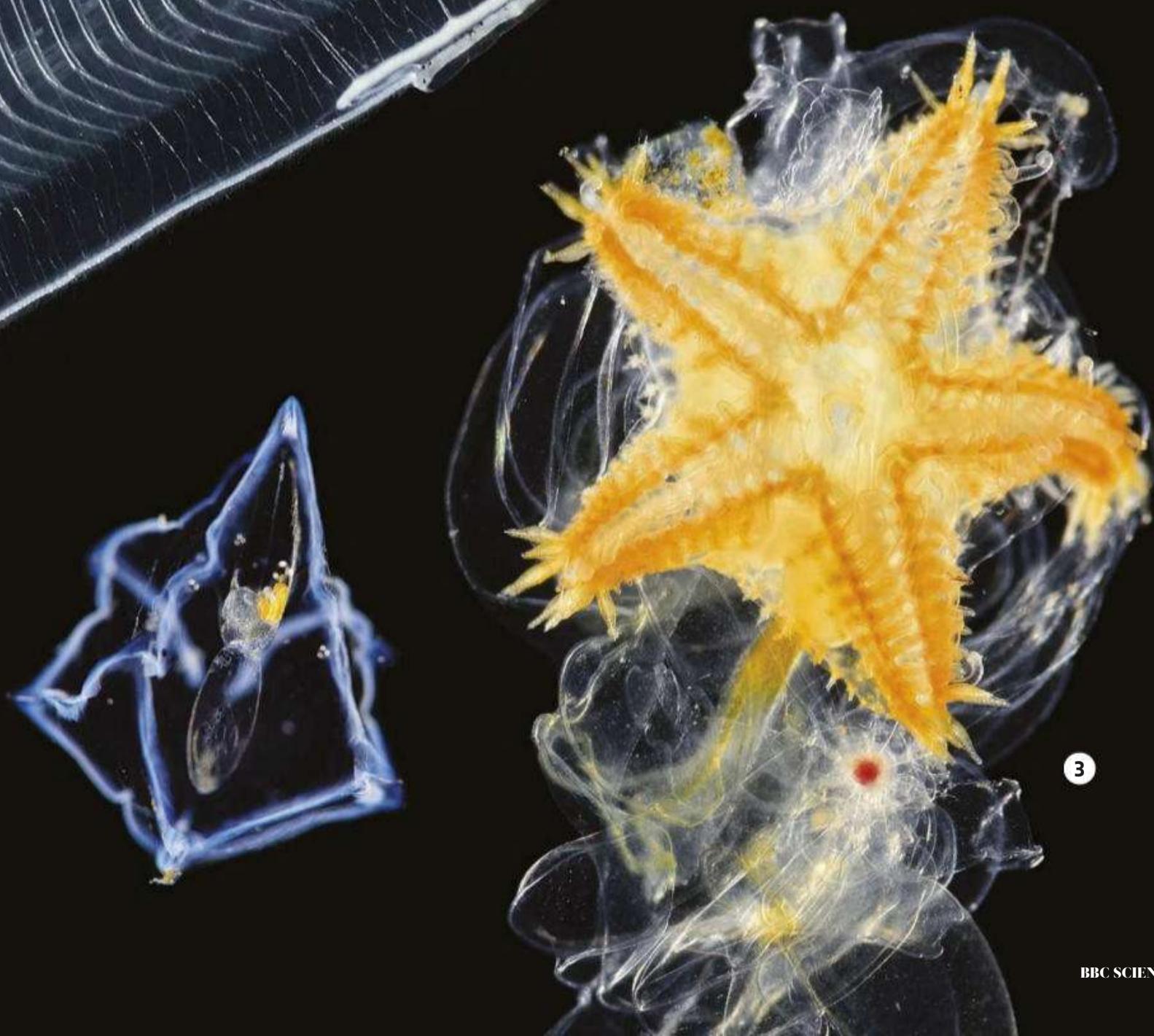




CLEARLY DIFFERENT

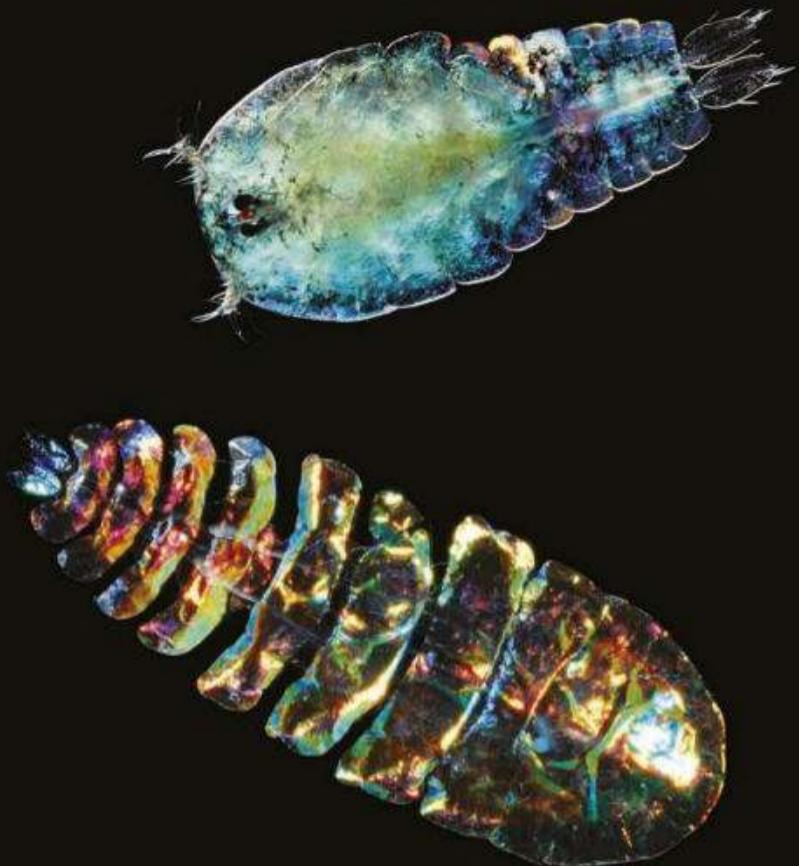
LEPTOCEPHALUS LARVA

Ocean animals often have early stages in their life cycles that are very different from their adult form. This leaf-like leptocephalus larva will eventually develop into an adult eel, transforming the shape of its body. Having a thin, see-through body as a larva may help it to survive the gauntlet of predators in the zooplankton as it grows. Because the larvae and adults look so different, larval forms were often described as different species from the adults, until marine biologists realised they were different stages of one life cycle.



3

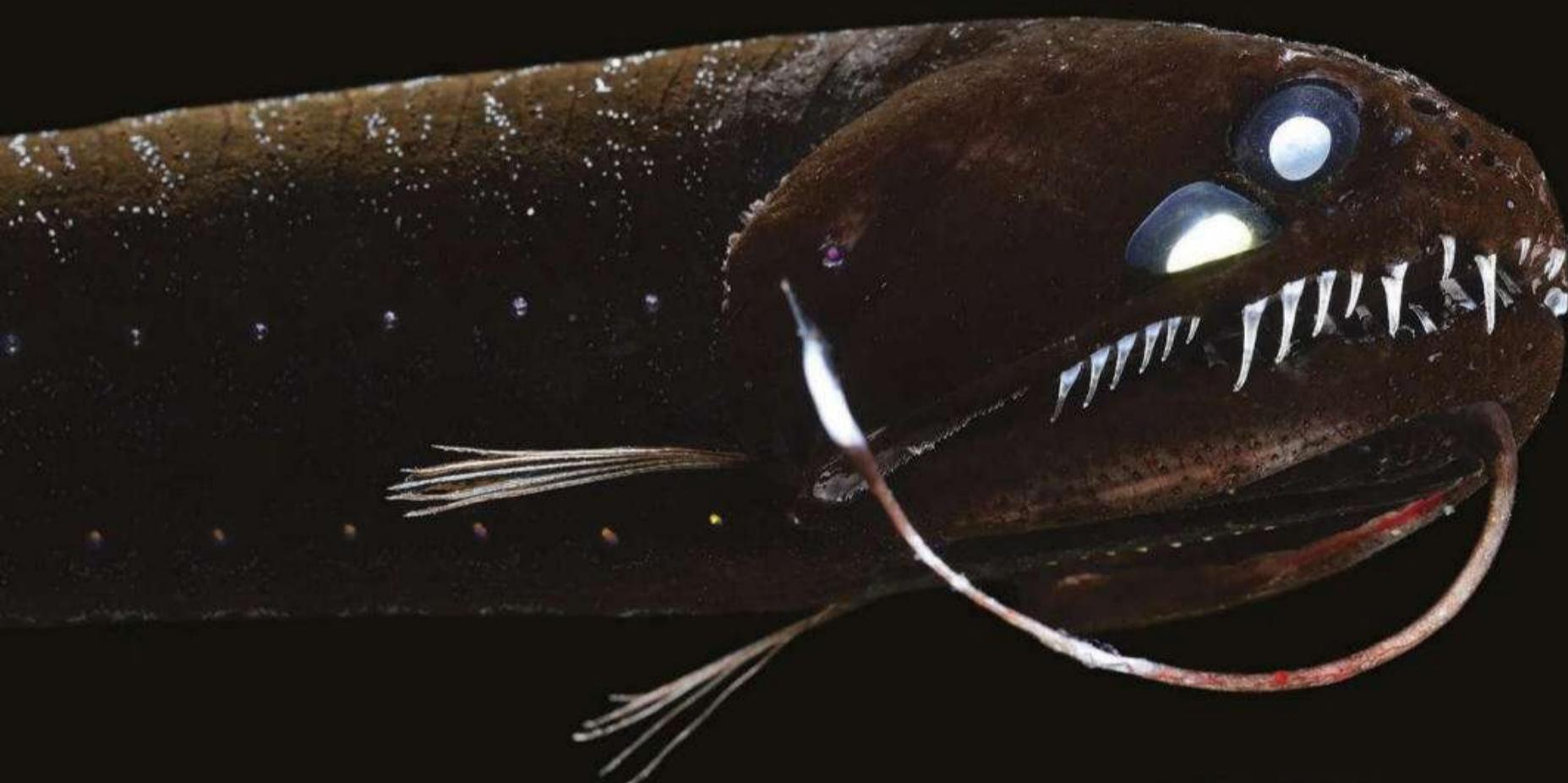
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SEA SAPPHIRES

← COPEPODS

Copepods are tiny crustaceans, typically only a millimetre or two in size, and are often eaten by deep-sea fishes such as the thread-tail and the stoplight loosejaw. Most copepods graze on microscopic algae that thrive near the ocean surface, and their faeces and dead bodies help to carry carbon into the deep below. But these 'sea sapphire' copepods are different: the females live as parasites inside drifting jelly animals called salps, while these colourful males swim free in the ocean. The males have tiny crystal plates in their skin that reflect blue light, giving them a glittering appearance.



LIGHTS IN THE DEEP

↑ DRAGONFISH & HATCHETFISH →

Like underwater fireflies, many deep-sea animals can produce spots or flashes of light, known as bioluminescence. In the twilight zone, the remnants of sunlight cast shadows that reveal animals to predators, so lots of species in this zone are speckled with lights for camouflage. The underside of the hatchetfish, for example, has bioluminescent organs that match the faint light coming from above, breaking up its silhouette.

Down in the midnight zone, animals such as the dragonfish use bioluminescent searchlights to find their prey. And throughout the deep ocean, creatures signal with lights to other members of the same species, to attract a mate, for example.





RED FOR DANGER

↑ STOPLIGHT LOOSEJAW

The stoplight loosejaw fish is one of the stealthiest predators in the deep. Its lower jaw is an open frame of bone with no fleshy floor across it, which means it can snap shut very quickly like a mousetrap. And it's called 'stoplight' because the bioluminescent organs near its eyes produce red light. Most bioluminescence in the deep ocean is blue, as that colour travels well through water, and the eyes of many deep-sea animals aren't sensitive to red light. But the stoplight loosejaw can see red, so it can light up its prey without alerting them to the danger.





NOW YOU SEE ME

← GLASS SQUID →

There are around 60 species of glass squid in the ocean, and they get their name from their transparent bodies – a neat trick to avoid casting a shadow that could be spotted by predators in the twilight zone. On the left is the juvenile of a lyre cranch squid. The two appendages sticking out from it, are eyes on long stalks. Those eyes are more opaque than the rest of its body, so each eye also has a bioluminescent organ to mask its shadow. But when this juvenile grows up, those stalks will disappear, and it will move down to live in the midnight zone as an adult.



MISMATCHED MOLLUSC

COCK-EYE SQUID

Squid in the deep ocean come in a range of sizes, from the Kraken-like giant squid that can stretch more than 10 metres to the tips of its longest tentacles, to tiddlers measuring about 15 centimetres long. And deep-sea squid come in a variety of shapes too: the cock-eye squid, also known as the strawberry squid, has one eye twice the size of the other. It swims in the twilight zone with the large eye looking up for shadows cast by potential prey, and the smaller eye keeping a lookout for possible predators below.





DENIZENS OF THE DEEP

↑ THREAD-TAIL FISH &
↖ BOXER SNIPE EEL

The thread-tail fish and the boxer snipe eel have long, thin, ribbon-like bodies. The thread-tail's body is about 30 centimetres long, with streamers twice as long on its tail, which gives this fish its name. Its other name is the 'tube-eye fish' thanks to the binocular-like lenses of its eyes, which are used to spot the shadows of prey in the twilight zone. So unusual is the tube-eye fish, that it's the only species in an entire taxonomic order. The boxer snipe eel grows to nearly 1.5 metres long, and feeds by sweeping its long jaws through the water, snagging the appendages of passing crustaceans on its fine teeth.



FOLLOW THE LIGHT

anglerfish

Life can be scarce in the dark depths, which is a problem when animals need to find a partner for mating. Hanging on to a potential mate is a good solution, and some deep-sea anglerfishes take that to extremes. The males are much smaller than the females, and when boy meets girl, he gives her body a kiss that lasts the rest of his life. The male's blood supply joins up with the female's through his lips, and he lives off her like a parasite while she catches prey with her bioluminescent lure. But the dangling male is handy accessory for the female to carry around, ready to fertilise her eggs when she releases them.



COMMENT

TURNING THE TIDE

Almost all of the world's oceans have been damaged by human activities such as pollution, industrial fishing and climate change. But how does this impact the deep ocean environment?

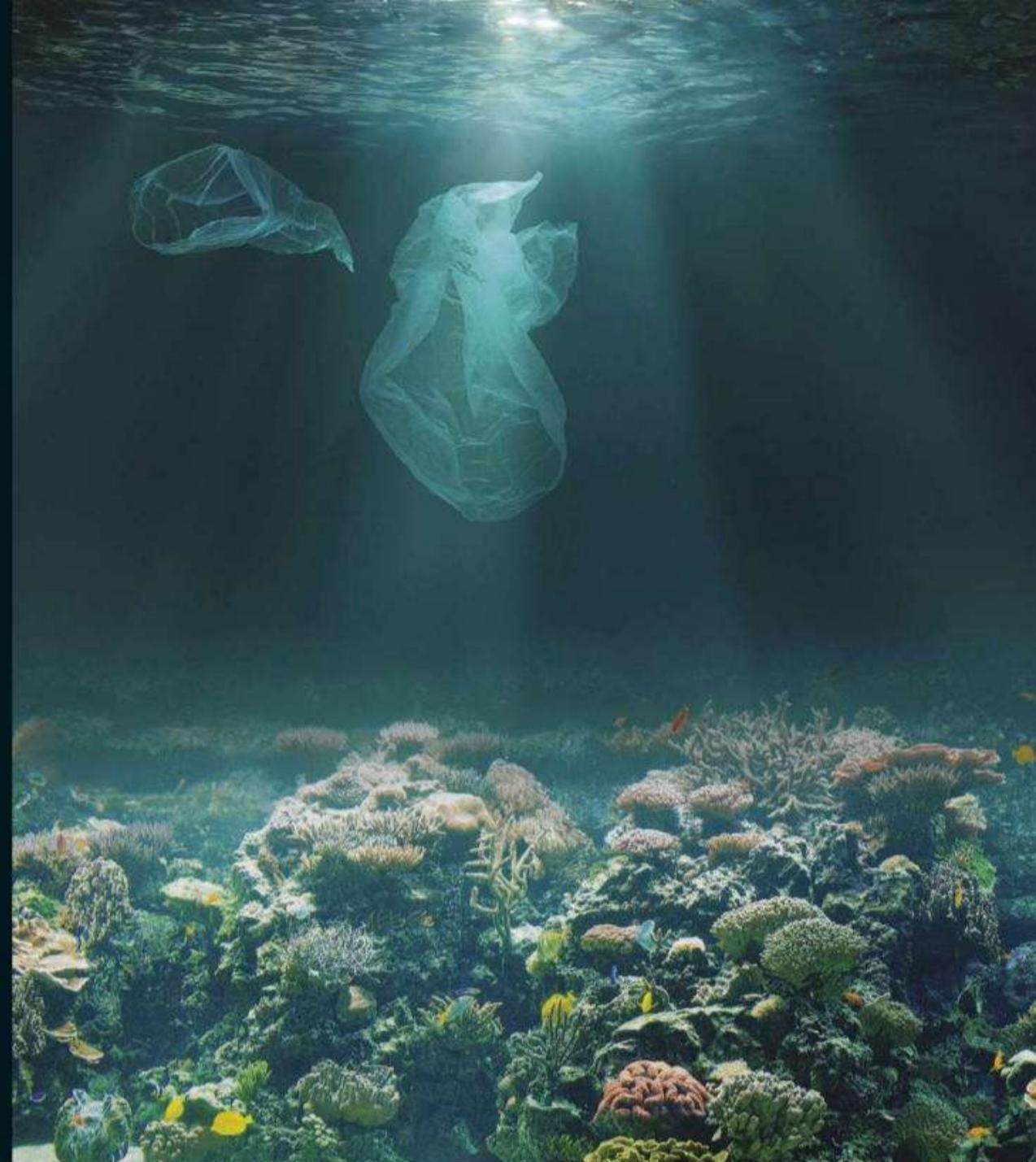
Shallow coral reefs and other habitats near the coast are on the front line when it comes to the effects of rubbish, climate change and overfishing, simply because they are closest to where we live. But the deep sea is also affected – it may be out-of-sight to us, but unfortunately it's not out-of-reach from the impacts of our lives.

When our rubbish ends up in the ocean, it doesn't just swirl about at the surface – even plastic bags eventually sink to litter the ocean floor, along with other items such as discarded fishing gear.

I've found rubbish almost everywhere I have explored the ocean floor, from five kilometres down in the Cayman Trench of the Caribbean, to the peaks of undersea mountains far from land in the Indian Ocean.

The tiny microplastic particles that we can't see from our deep-diving vehicles are everywhere, too. They have been detected at the bottom of the deepest ocean trenches, and even found in the guts of some of the animals there. Even if those particles are not toxic to the deep-sea animals that swallow them, they have no food value. The animals that eat them may get less energy from each mouthful, which could leave them less able to escape from a predator, or producing fewer offspring, changing the fate of their population.

Industrial fishing also has an



“Microplastics have been detected at the bottom of the deepest ocean trenches”

impact on deep-sea life, as fisheries have moved into deeper waters. Some deep-sea fish take decades to grow to full adult size and reproduce, which can make them vulnerable to overfishing if they are taken from the ocean more quickly than their population can replenish itself. And bottom-trawling, where fishing gear is dragged across the seafloor, can wipe out seafloor habitats such as deep-sea coral reefs and sponge gardens, which are home to many other species as well as deep-sea fish. Deep-sea fishing is perhaps easier to tackle than other impacts, however: the EU has now banned deep-sea bottom-trawling in its waters, and there are certification schemes to

help us choose fish from sustainably managed fisheries if we want to buy them.

But the most widespread human impact on the deep ocean comes from climate change. Most of the additional heat trapped in the atmosphere by our greenhouse gas emissions is absorbed by ocean, altering its circulation. In particular, vast currents of cold water that sink from the polar areas into the deep ocean are getting weaker. Those currents carry oxygen from the atmosphere into the deep, and all the animals in the deep sea depend on that flow of oxygen-rich water. There are areas where oxygen is becoming scarce in the deep ocean, forcing animals to move elsewhere if they can.

Although the deep ocean seems like an alien and remote place, its deepest point is less than 11 kilometres from the surface – about the same as a two-hour walk on land. It may be hidden from us by a watery veil, but it's very much part of our world – and its future is in our hands. **SF**

by DR JON COPLEY

Jon is an associate professor of ocean exploration and public engagement at the University of Southampton. He specialises in deep-sea environments and has climbed inside submersibles to explore this alien world.

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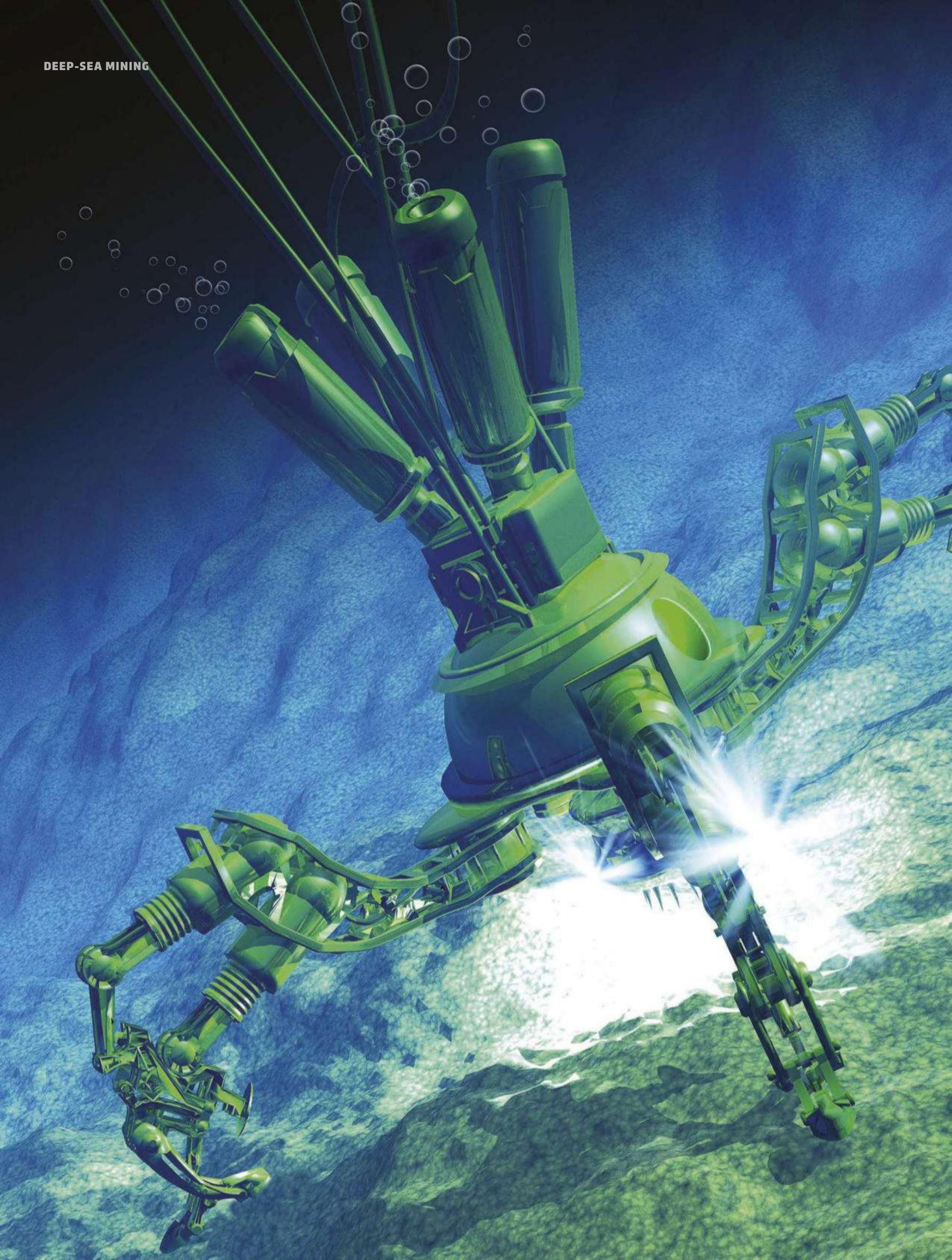
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DEEP-SEA MINING



CHASING THE DEPTHS



THE DEEP SEA CONTAINS A TREASURE
TROVE OF PRECIOUS RESOURCES THAT
PEOPLE WANT TO MINE. BUT ARE
REGULATIONS IN PLACE TO PROTECT
THE DELICATE ENVIRONMENT FROM
THIS RACE TO THE BOTTOM?

WORDS DR HELEN SCALES

every time you pick up your smartphone, you hold in your hand a veritable periodic table of elements. Among the metals under the casing, there's cobalt, nickel and indium, plus traces of 16 of the 17 so-called rare earth metals. They're all dug up in mines dotted across the globe, from the Democratic Republic of Congo to the Philippines, Chile and China. One day, perhaps in the not too distant future, smartphones could contain metals that come not from land but from the deep sea.

Mining the deep isn't a new idea. For several decades, mining corporations have eyed up the mineral riches that lie in Davy Jones's Locker. But it's always been too expensive to operate machinery kilometres beneath the waves, and metal prices are too unsteady to make it worthwhile. Now, though, the first deep-sea mines are getting closer to opening.

In 2018, a test of deep-sea mining methods was carried out in the waters off Japan. Then in 2019, there was a failed attempt to open the world's first commercial deep-sea mine off Papua New Guinea. Plus, there's growing interest in mining vast swathes of open ocean, known as the high seas, that lie far from shore and no countries own. Currently, mining corporations are prospecting 1.3 million square kilometres of the high seas, roughly the area of Alaska. Before any mines can open, however, a new rule book needs to be written, laying down international regulations on how mining will operate.

The rules that book will contain are currently being negotiated with the aim of releasing a final list. When that happens, the first seabed mines in the high seas could start to operate.

TECH'S DEEPENING REACH

The main targets for deep-sea mining are potato-sized rocks, known as nodules, that lie scattered across flat abyssal plains. Miners are also prospecting underwater mountains, called seamounts, and the tall chimneys of hydrothermal vents. The extraction system will involve gargantuan machinery bristling with enormous drill bits and operating remotely, thousands of metres down, to scrape off the metal-rich crusts of seamounts and crush vent chimneys.

Machines with giant caterpillar tracks will crawl across the seabed scooping up nodules. Then, the rocky slurry will be pumped up to ships on the surface for processing.

Driving this new rush for the deep is the tech industry's rising demand for metals, plus fears that traditional sources from land-based mines could be running low. Some experts also claim that tackling climate change and phasing out fossil fuels will be impossible unless the deep sea is mined for metals to make solar panels, wind turbines and electric car batteries – a single car battery currently needs nine kilograms of cobalt. As a consequence, corporations are keen to secure new supplies of metals.

"It's a few people sensing an opportunity that, if they're the first movers, they can really get ahead of the game," says Kristina Gjerde, senior high seas policy advisor to the International Union for Conservation of Nature (IUCN) and co-lead for the Deep Ocean Stewardship Initiative.

There's more at stake than just the metals lodged inside these deep-sea deposits, though.

Nodules, seamounts and hydrothermal vents are home to extraordinary life forms unlike anything we see on land, and only a fraction have so far been discovered and studied.

"Most people view the ocean in this two-dimensional way," says Dr Diva Amon, a deep-sea biologist at the Natural History Museum in London. "It's just a blue expanse." And yet, covering 60 per cent of the Earth's surface and four kilometres deep

on average, it forms the biggest living space on the planet. Amon describes a recently discovered Pacific seamount covered in corals and sponges, which live for thousands of years. "It looks like something out of a Dr Seuss book," she says.

As well as the biological wonders it's home to, the deep sea regulates the climate, absorbs roughly a third of humanity's carbon emissions, supports fisheries that feed millions of people and could hold secrets to new pharmaceuticals. "Our deep sea is essentially responsible for keeping us alive," says Amon.

WHAT'S MINE IS YOURS

Complicating matters is the fact that the deep sea legally belongs to nobody and everybody at the same ➤



ABOVE
Polymetallic nodules protrude from the muddy bed of the Clarion-Clipperton Zone. Both the mud and the nodules serve as habitats for the rare forms of sealife that dwell there

RIGHT Deep-sea biologist Dr Diva Amon has catalogued the marine life in regions of interest to miners

PROTECTING THE CCZ

Miners have their eyes on the bounty of the Clarion-Clipperton Fracture Zone

At the bottom of the Pacific Ocean between California and Hawaii, stretches the Clarion-Clipperton Fracture Zone (CCZ), a muddy plain measuring six million square kilometres that's covered in trillions of polymetallic nodules. It's a major focus for deep-sea mining prospecting.

Dr Diva Amon was part of a team that catalogued a wealth of sea life in parts of the CCZ where scientists had never been before. "Just over half of all the animals that we brought up were completely new to science," she says. Amon and her colleagues revealed this to be one of the most diverse places in the deep sea.

The nodules themselves also form an important habitat. They're the only hard surface available for deep-sea corals and sponges to grow on, and scientists have spied octopuses laying eggs on the stalks of these sponges.

Recently, another research team found thousands of grooves in the muddy seabed 4,000m below the surface that could be being dug by deep-diving whales. If whales are hunting for food in the floor of the CCZ, it adds another challenge to making sure mining doesn't impact the ecosystem.

CRAIG SMITH/DIVA AMON/ABYSSLINE PROJECT, NOVUS SELECT

LOCATION OF CCZ

DEEP-SEA MINING TARGETS

Resource-rich locations being scouted by miners

Polymetallic nodules

LOCATION: Abyssal plains

MAIN DEPOSITS: Clarion-Clipperton Fracture Zone and the Peru Basin in the Pacific

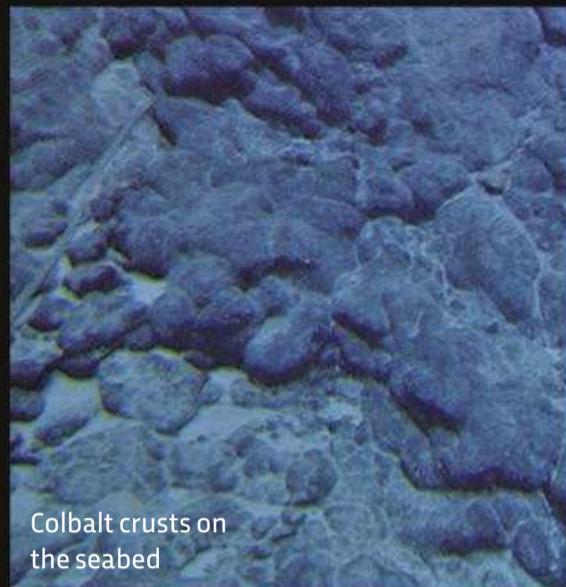
DEPTH: 4,000-5,500m

METALS: Manganese, nickel, cobalt, copper, plus traces of molybdenum, lithium and rare earth metals (REMs)

KEY FEATURE: 5-10cm spherical rocks that grow as metals settle out of the water at a rate of a few millimetres per million years

WHAT LIVES THERE: Octopuses, corals, sponges, brittle stars, sea cucumbers and maybe foraging whales

Polymetallic nodules contain various metals



Cobalt crusts on the seabed

Cobalt-rich crusts

LOCATION: Seamounts

MAIN DEPOSITS: Western equatorial Pacific

DEPTH: 800-2,500m

METALS: Manganese, cobalt, copper and nickel, plus traces of REMs

KEY FEATURE: The metal-rich crusts grow around 1-5mm per million years

WHAT LIVES THERE: Corals, sponges, starfish, sea urchins, long-lived fish



Hydrothermal vents are unique environments

Seafloor massive sulphides

LOCATION: Hydrothermal vents

MAIN DEPOSITS: Mid-ocean ridges, subduction zones

DEPTH: 800-5,000m

METALS: Copper, zinc, lead, cobalt, silver and gold, plus traces of REMs

KEY FEATURE: Around 80 per cent of animals living on hydrothermal vents are found nowhere else on the planet. It's also thought life on Earth could have first evolved in hydrothermal vents

WHAT LIVES THERE: Yeti crabs, Hoff crabs, octopuses, scaly-foot gastropods, giant tube worms

time. The United Nations Law of the Sea Treaty declares the seabed beyond national boundaries as the 'Common heritage of humankind'. It can only be used for peaceful purposes and part of any profits must be shared, especially among poorer nations. Similar treaties apply to Antarctica, the Moon and space.

The International Seabed Authority (ISA), a small organisation based in Kingston, Jamaica, is charged with looking after the seabed on behalf of humanity. It's up to the ISA to decide how to share out any wealth generated in the deep, something that needs to be worked out before any mines open. The ISA is also legally bound to ensure that mining causes no major ecological damage. The impacts of mining on deep-sea life and the vital services it provides are not yet fully understood, although chances are they could be severe and, in some cases, irreversible. Nodules and seamount crusts take millions of years to form and mining machinery will kick up muddy plumes that could drift tens and hundreds of kilometres, smothering delicate creatures on the seabed, as well as in open water.

"We need that fundamental science to be able to make informed decisions about whether we should or should not go ahead with deep-sea mining," says Amon. Plans are being drawn up to protect delicate

deep-sea ecosystems including areas that will be off-limits to mining, but the science isn't clear on whether these measures will work.

Amon and many others think that the rush to open mines should slow down while more science is gathered. In 2018, the European Parliament called for a global moratorium on deep-sea mining until the risks are fully weighed up. "We can't manage what we don't understand and we can't protect what we don't know," says Amon.

It's also unclear just how important the deep-sea mines will be in supplying the world with metals. "I think we do need to ask critical questions," says Gjerde. "Is this the time to go into the vast unknown in order to get some relatively short-lived metals that we think we need for the green revolution?"

Eventually, we could all end up facing a choice in the gadgets and cars we buy. Perhaps, in the years to come, a circular economy will develop in which metals won't be used just once then thrown away, but recycled and reused many times. Or maybe we'll see labels on products showing the origins of metals used inside them – perhaps brown labels for metals from mines on land and blue labels for metals brought up many kilometres from the bottom of the sea. **SF**

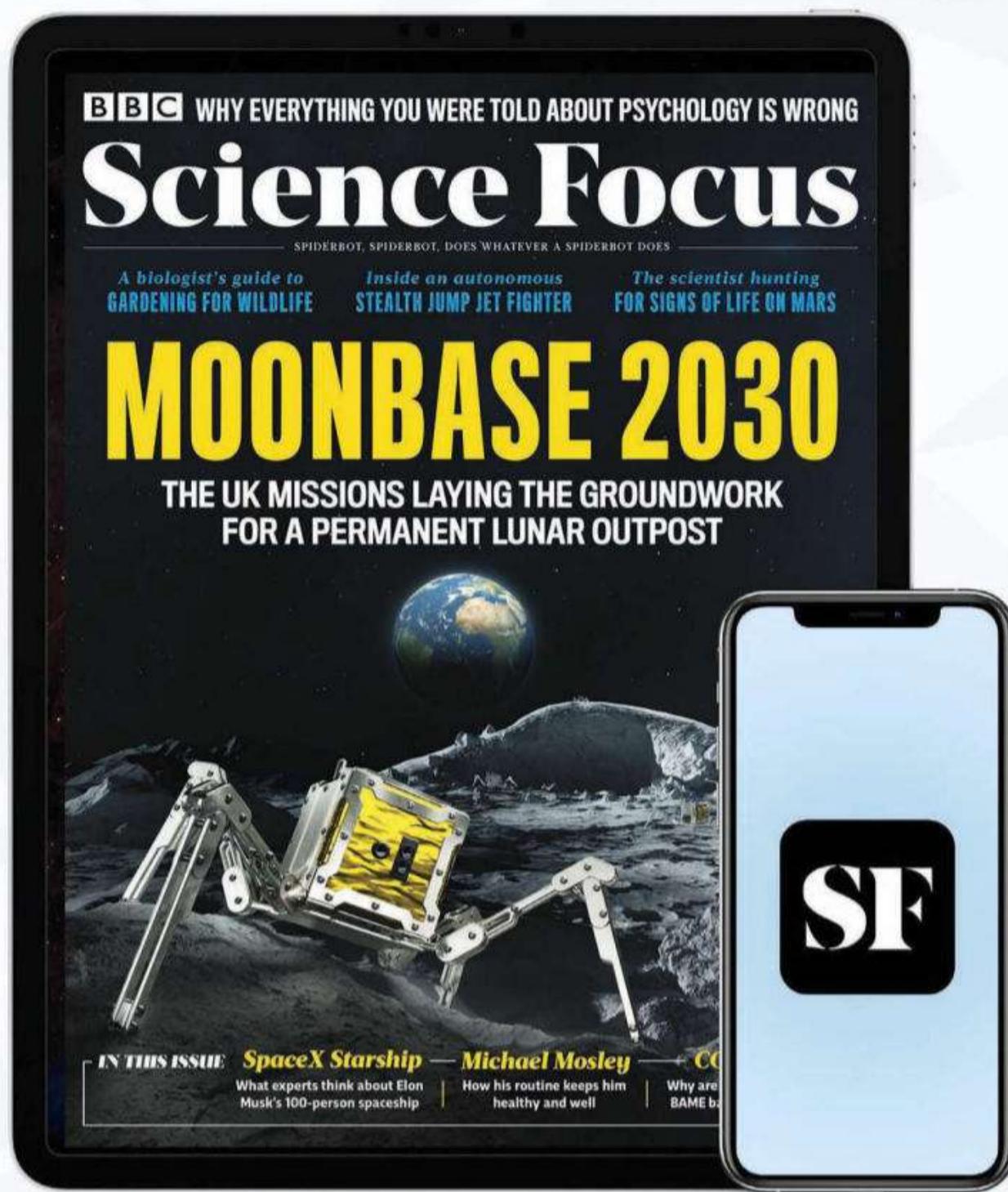
by DR HELEN SCALES

Helen is a marine biologist, broadcaster and author. Her next book, *The Sea Beneath Us* (£16.99, Bloomsbury Sigma), will be out in February 2021.

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THE PLASTIC AGE

In recent years we've had an epiphany: our lives and the planet are literally filling up with plastic. Now that we're starting to get a grip on the scale of the problem, what can we do about it?

by DR HELEN SCALES

Maybe it was the baby sperm whale on the BBC's *Blue Planet II* with a plastic bucket snagged in its mouth. Or the photograph of a seahorse clutching a drifting cotton bud, or perhaps a visit to a rubbish-strewn beach? Whatever it was that awakened you to the problem, there's no doubt that in recent years more people than ever have been shocked into noticing the issue of plastic pollution.

As scientists venture out to gauge the scale of the problem, the plastic facts are being laid bare: a trillion plastic fragments frozen into the Arctic sea ice; a plastic bag at the bottom of the Mariana Trench, almost 11 kilometres down at the oceans' deepest point; each square metre of a riverbed in Manchester infested with half a billion microplastic particles – the highest concentration measured anywhere on the planet so far. Plastic is showing up in the food we eat, the water we drink, even the air we breathe. The details quickly become overwhelming but the message is loud and clear: the world, and our daily lives, are filling up with plastic. What's less clear is what damage this is causing to wildlife and people, and what we should do about it.

"Our picture of the environmental impact is still

patchy," says Dr Richard Thompson, professor of marine biology at Plymouth University, who published a landmark paper in 2004 revealing the widespread pollution of the oceans with microplastics, under 5mm in size. A major health concern is the possibility that those plastic fragments percolate through ocean food webs and end up in the seafood we eat. Many studies have already shown that microplastics are eaten by hundreds of aquatic animals, including fish, krill, plankton, seabirds, crabs, worms and corals. Some species even seem to prefer plastic over their normal food, perhaps because of the way it smells. And it's no surprise that having a gut filled with indigestible plastic tends to make life difficult: animals grow more slowly, run down their energy reserves and reproduce less. Many end up dying.

"Each m² of a riverbed in Manchester has half a billion microplastic particles"

get passed on as animals eat each other. Does a shark or a seal inherit a plastic payload from their prey? Several studies are beginning to suggest this could be the case. In the Celtic Sea, out of a sample of 109 plaice, just over half had fragments of microplastics in their guts. Researchers also found similar traces inside sand eels, making a tentative link between these plankton-feeders and the flatfish that eat ➤



As more plastic finds its way into the oceans, more of it ends up in the intestines of sea life

THE NEW 'PLASTICS'

In the next few years we could start seeing traditional oil-based plastics increasingly replaced by biodegradable plastics, including some made from unusual materials

SHRIMP SHELLS AND SILK

A major waste from the food industry is chitin, the main component of shrimp, crab and lobster shells. Researchers at Harvard University have combined it with silk protein to form a degradable plastic they've named Shrilk.



MANGOS

Mango seeds and skins are being investigated as possible sources of bioplastics for use in plastic bottles and cups.



WOOD

Lignin, a tough material from trees, is a by-product in the paper-making industry that's usually burned. Scientists are now feeding it to genetically-modified bacteria, which break it down into molecules for making bioplastics.



SEAWEED

Dutch designers have developed a bioplastic made from algae, which can be used in 3D printers.



MUSHROOMS

A New York-based firm is developing foam packaging from the thread-like roots (called mycelium) of mushrooms, as a replacement for polystyrene.



HAIR

An art student in London has made a chair from human hair. A single chair was made from three full bin bags of hair, swept from the floors of hairdressers and glued together with another bioplastic.



“It’s really important that we make the right decisions now and we don’t jump to knee-jerk reactions”



► them. In Australia, scientists fed microplastics to little, beach-dwelling crustaceans called sand hoppers, then fed those sand hoppers to small fish called gobies. Again, the plastics were passed one step up the food chain. Whether this has any lasting impact on the sand eels, plaice or gobies is an unresolved matter. And while we’re still a long way off understanding how microplastics impact simple duos of predators and prey, we’re even further from getting a handle on what’s going on across entire, complex ecosystems.

COMING BACK TO HAUNT US

If plastics are contaminating aquatic food webs, are they also getting into our food? There’s no doubt that when you eat a bowl of moules marinière, you could be consuming microplastics that the mussels pick up as they filter seawater. A recent study found plastics inside mussels on supermarket shelves and living all around the British coasts. The question is, does eating them do us any harm? Well, besides the plastics themselves, there’s the chemicals they’re coated in. Chemicals such as phthalates and bisphenol A are added to plastics to make them more flexible, transparent and durable, and when they leach off they’re known to disrupt hormones in vertebrates.

As yet, no major medical horrors have been uncovered, but it’s not easy proving a link between health problems and plastics creeping into our diets. “If it was suddenly shown that plastic particles, in some shape, form or dimension, had the same effect as asbestos, that would, of course, accelerate the process towards



NANOPLASTICS

A bigger problem than microplastics?

Nanoplastics smaller than a micrometre in size (one micrometre = one-thousandth of a millimetre) could be floating through the oceans and piling up on the seabed, but at the moment there's no way of detecting them. Scientists are developing automated machines to trace the chemical signatures of these tiny plastics, so we should know more soon. Already there are fears that nanoplastics could cause even bigger problems than microplastics because they're likely to hold more chemical contaminants on their relatively large surface area and there's a possibility they could get inside living cells. In a lab study, when zebrafish were fed nanoplastics, the particles moved into the fishes' blood and built up in their nervous systems. This changed their behaviour and possibly caused brain damage: the fish explored their surroundings less and ate more slowly. Contaminated female zebrafish even passed on nanoplastics to their young. Another study shows that animals may produce nanoplastics. Antarctic krill, after being fed fluorescent green microplastics, ground them down in their guts and glowing nanoplastic particles appeared in their faeces. It seems likely that krill are doing something similar in the wild.

change," says Thompson. "We just don't know that at the moment."

Thompson worries that if we wait until we fully understand the environmental and human harm of ocean plastics, then decision-makers may rush towards solutions that look tempting but could end up causing more trouble. "It's really important that we make the right decisions now and we don't jump to knee-jerk reactions." He points towards the focus on banning plastic drinking straws as a misguided effort. "It's great to encourage people to do without them," he says, "but on its own it isn't going to solve the problem and some would argue it's a bit of a distraction."

Thompson is convinced the key to finding the right ways to solving plastic pollution will be to bring together teams of experts from different disciplines. It won't just be ecologists and toxicologists studying the impacts of plastics, but material scientists working on making them easier to reuse and recycle, and psychologists who understand what changes people's habits. "We need

ABOVE Water samples can show the extent of the spread of microplastics in the oceans

BETWEEN Mussels feed by filtering seawater and so inadvertently consume microplastics

to change our relationship with plastic," he says.

Thompson takes a positive outlook and believes we've reached a crucial stage. "Things have never been as aligned as they are now," he says. Not only are the public aware and demanding changes, he points out, but policymakers are eager to respond to those demands, as are industry leaders, either because they see a financial threat if they don't act, or because they see an opportunity if they do.

There's no doubt that the public are engaging with the plastic debate more than any other modern environmental threats. "People can see this marine litter and they can identify with it," Thompson says. Of course, there are other, less visible problems to deal with, such as climate change, but he argues that solving the plastic problem could set a good example of how to get things right. He likens ocean plastics to the issue of CFCs and the ozone layer 30 years ago. "There's an environmental challenge here," he says. "I think it's a problem we can solve." **SF**



by **DR HELEN SCALES**
(@helenscales)
Helen is a marine biologist, broadcaster and author. Her next book, *The Sea Beneath Us* (£16.99, Bloomsbury Sigma), will be out in February 2021.

HACK YOUR SHOPPING

MANY OF US ARE LOOKING TO REDUCE THE AMOUNT OF SINGLE-USE PLASTIC THAT ENDS UP IN OUR WEEKLY SHOP. HERE ARE A FEW EASY IDEAS TO HELP YOU KICK THE PLASTIC HABIT

NAKED FRUIT & VEG

Who needs their apples and bananas in a plastic packet? Take a canvas bag, and grab individual fruit and veg. Loose stuff is often cheaper, so you'll save money, too!

JUMBO SNACKS

Multipacks contain lots of little plastic packets. So go for bigger, single packets of popcorn, crisps and nuts that you can reseal with a peg. Just promise not to pig out!

ECO REFILL

Grabbing a coffee on the way home? Use a reusable cup. If you prefer water, carry a reusable bottle and fill up on the fly. The *Refill* app helps you locate free refill stations.

GLASS JARS

Pick peanut butter, spreads and sauces in glass jars and bottles that can be reused or recycled. Or, why not impress your colleagues and learn how to make your own jam?

OVER THE COUNTER

Get your meat or cheese at the counter, where it's often sold with less packaging. Some supermarkets will even let you take your own reusable containers.

SHOP LOCAL

Check out your local farm or farmers market! What can you buy directly from source? You'll be supporting local businesses and buying fresh without the packaging.





Watch *Plastic Not Fantastic*,
a series of three episodes
available now on iPlayer.
bit.ly/plastic-not-fantastic



In October 2019,
The Ocean
Cleanup's system
collected plastic
from the Great
Pacific Garbage
Patch for the first
time. But is this
the best way of
dealing with the
plastic problem?

by ALICE LIPSCOMBE-
SOUTHWELL

TROUB WATERS



There was a time when many of us accepted a straw in our Friday-night cocktail without a second thought. But in October 2017, *Blue Planet II* hit our screens, opening eyes to the damage that plastic waste is causing to the world's oceans. While conservationists and marine scientists had long been aware of the issue, it was this series that brought the problem hurtling into public consciousness. Since then, many of us have tried to restrict our use of single-use plastics, while governments have been urged to take action – in the UK alone, microbeads in toiletries have already been banned, and from October 2020 plastic stirrers and straws will be restricted. Currently, around 380 million tonnes of

plastic are produced each year – a large proportion of it single-use – and a whopping 12 million tonnes of the stuff enters our oceans, but following its movements is a tricky task. “There are definitely hotspots, such as gyres [see box, p80], but it is also predicted that a lot of plastic sinks. We are doing research at the moment, tracking litter’s movement,” says the University of Plymouth’s Imogen Napper, who studies plastic pollution in the marine environment.

PICKING UP THE PIECES

So what can be done to get plastics out of the ocean? One organisation that’s trying to tackle the problem is Netherlands-based The Ocean Cleanup, which was set up by inventor Boyan ➤

L.E.D.



The Ocean Cleanup's system may collect plastic, but is it inadvertently trapping marine life, too?

• Slat in 2013, when he was just 18 years old. It wants to deploy its 'passive systems' into the five major ocean gyres, to collect plastic for recycling.

While its first system failed in December 2018, in October 2019 the organisation triumphed. After design tweaks and modifications, its latest device, called System 001/B, successfully captured and retained plastic debris from the infamous Great Pacific Garbage Patch in the North Pacific gyre. In a press release, The Ocean Cleanup claimed that its system even scooped out microplastics as small as 1mm. The organisation estimates that a fleet of its systems could clear half of the Great Pacific Garbage Patch in five years.

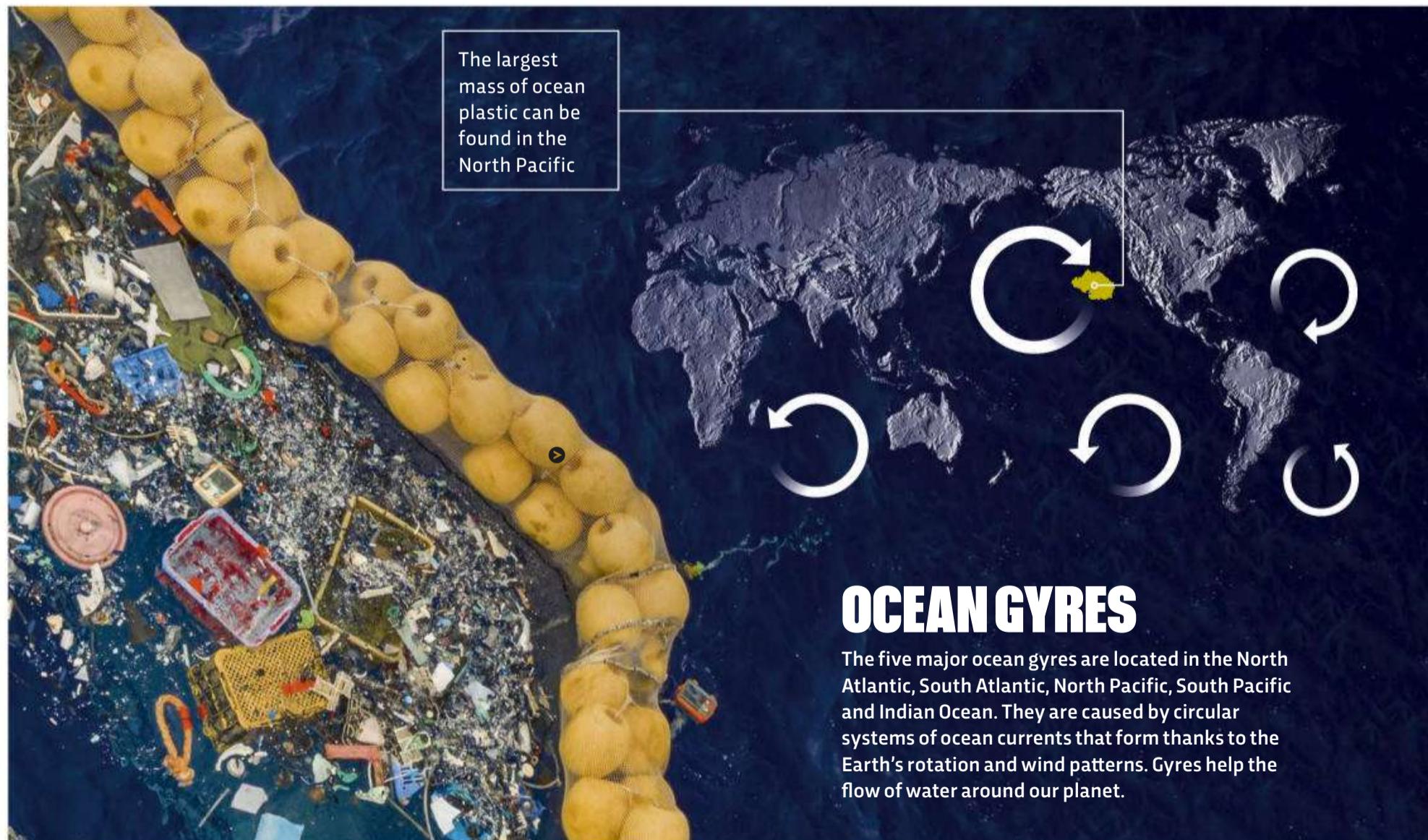
Despite its name, the Great Pacific Garbage Patch isn't a huge floating landfill site that you could stroll across if the mood took you. Instead, it's like a rather unpleasant minestrone soup – but in place of chunks of vegetables and pasta, the water is filled with assorted plastic waste, including 'microplastics' (smaller than 5mm). Plastic does not fully degrade like organic waste; instead, the action of the ocean and sunlight causes it to break down into tinier and tinier bits.

While it's easy to understand how a plastic bag or piece of fishing line could block the guts of a seabird or turtle if they mistook it for food, less is known about how microplastics affect the ocean ecosystems, and it's currently an important area of research for scientists. The size of microplastics means they are small enough to make a tasty mouthful for the tiniest creatures, which potentially harms the organism and also means that the chemicals associated with the plastic will accumulate up the food-chain.

System 001/B may be successfully capturing plastics, but the University of North Carolina Asheville's Rebecca Helm, an assistant professor who specialises

in open-ocean ecosystems, says that it is catching many 'neuston' at the same time. The neuston is a group of organisms such as snails, sea slugs and plankton that live at, or just below, the ocean surface. Sometimes, these invertebrates occur in such enormous numbers that they're like a living island. "It's really the only ecosystem that exists firmly wedged between the atmosphere and the ocean," says Helm. "It's preyed upon by birds" ➤

"EXPERTS AGREE THAT THE VAST MAJORITY OF OCEAN PLASTIC ARRIVES VIA RIVERS"





THE OCEAN CLEANUP SYSTEM 001/B

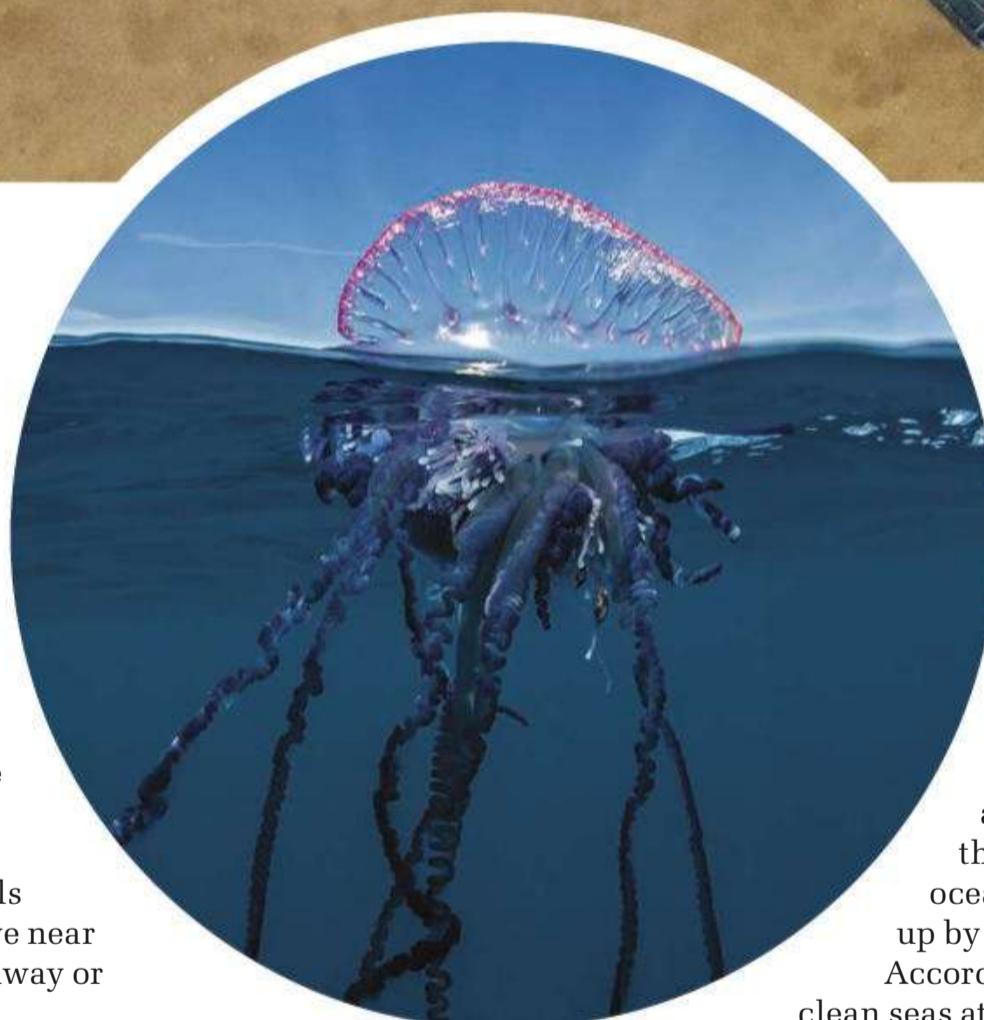
This system moves with the currents, winds and waves – just like plastic does. Its design consists of a 600m-long floating boom ① that sits on the water's surface, and a 3m skirt ② that sits below to prevent plastics from escaping underneath. Meanwhile, a parachute-like sea anchor ③ slows down the system, so that plastics can be captured. A support vessel will periodically visit the system to take the collected plastic for recycling ④.



TOP The Ocean Cleanup can collect tiny plastic pieces (left); the supply ship that removes the collected plastic (centre); Boyan Slat, CEO of The Ocean Cleanup (right)

INTERCEPTOR: HOW IT WORKS

1 The solar-powered Interceptor is located in a river. Floating barriers divert debris into the mouth of the system. 2 & 3 A conveyor belt then extracts the rubbish from the water and onto a shuttle, which will place the waste into one of six bins located on a barge. 4 When the Interceptor is full, it will send a message to local waste operators and the barge is brought to shore, so the waste can be recycled. The empty barge is then reinstalled onto the Interceptor, ready to be filled again.



Portuguese man-of-war are part of the neuston

• from above – there are a lot of seabirds that eat neuston – and also animals from below.”

This ecosystem is still poorly understood, and, according to Helm, there might not be any clear way that The Ocean Cleanup’s system could be adapted so it wouldn’t be impactful. “The reality is we don’t know if these animals are always mixed with the plastic or only some of the time,” she says. As these animals are soft-bodied, buoyant and live near the surface, they cannot swim away or escape if they get stuck.

The Ocean Cleanup (which did not respond to requests for comment), states on its website that it has carried out extensive observation campaigns to understand how System 001 might interact with marine life, and that “no substantial interference with the ocean ecosystem were observed; nor did we observe any entanglement or entrapment of marine animals.” It also pledges to monitor presence of marine life before plastic is lifted out of the water.

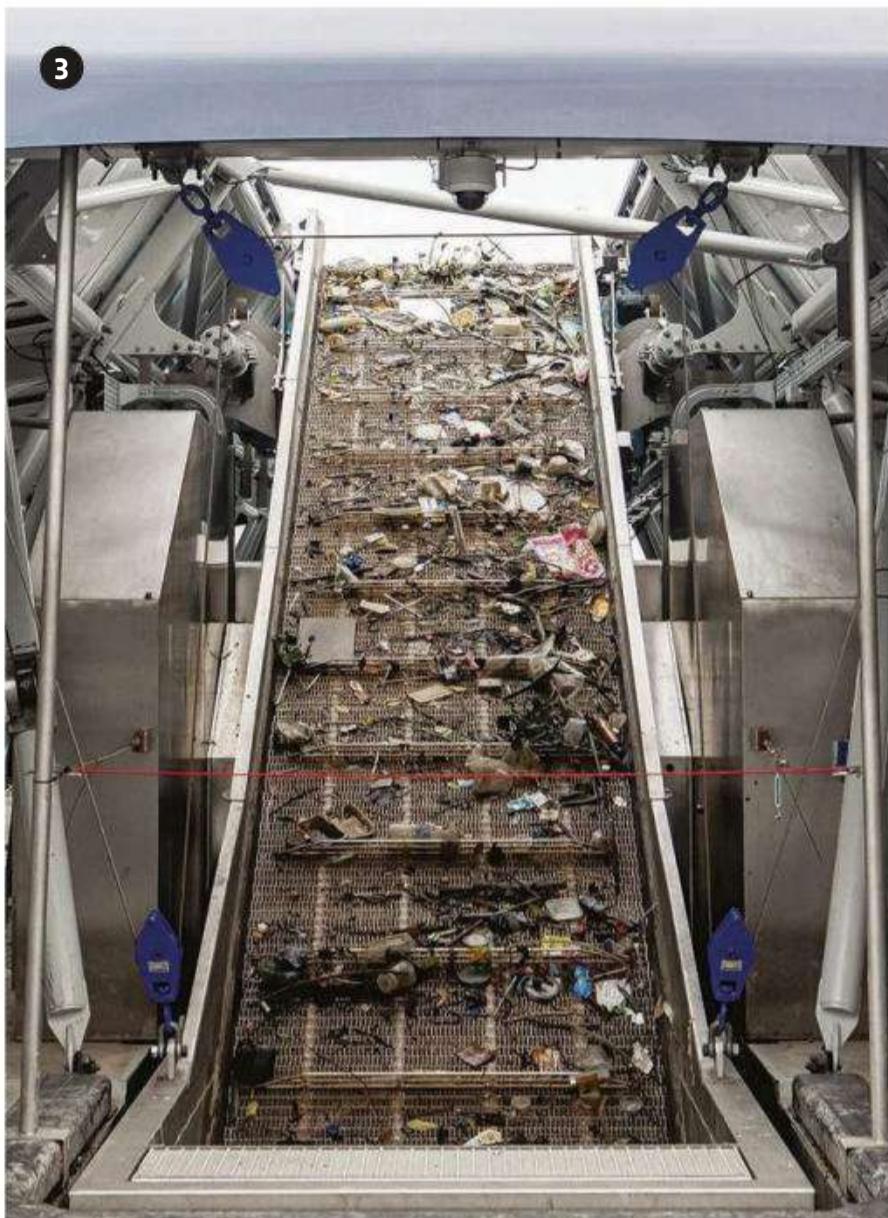
SCRATCHING THE SURFACE

Some experts wonder why The Ocean Cleanup is focusing its efforts on the ocean surface in the first place. A 2016 study by environmental consultancy Eunomia found that just 1 per cent of marine plastics are at the ocean surface, while 94 per cent ends up on the seabed. In fact, plastics are almost ubiquitous and can be found locked within the ice at the poles, lurking in the ocean trenches and can be scooped up by the handful at the seaside.

According to Laura Foster, head of clean seas at the Marine Conservation

Society, we should be concentrating our efforts on reducing our production of plastics, rather than clearing up rubbish in the ocean. “One of the main issues with The Ocean Cleanup is that it supports big industry’s narrative that ocean plastic is a litter problem, rather than a production problem,” she says. “Cleaning up in the current situation has been compared to trying to deal with an overflowing bath with a teaspoon... the solution is found by turning off the taps!”

Napper agrees that we need to reduce our use of plastics, but also says that the best way to prevent



plastic reaching the ocean is to stop it from land. "Land-based sources are the biggest contributor to plastic in the ocean," she says. "We also need to identify the pathway from land into the ocean. We are currently researching major river systems to understand this movement."

And The Ocean Cleanup has an answer for that. Back in October 2019, the team launched the Interceptor, an autonomous system that collects plastic from rivers before it reaches the sea. So far, Interceptors have been set up in Jakarta (Indonesia), Klang (Malaysia), Can Tho (Vietnam) and the Dominican Republic, with plans to install in Los Angeles and Thailand soon. While estimates vary, experts agree that the vast majority – up to 95 per cent – of ocean plastic arrives via rivers. The Ocean Cleanup says just one Interceptor can scoop up 50,000kg of plastic per day, and the team has given itself the goal of installing the systems in 1,000 of the most polluting rivers by 2025. "I'm really happy The Ocean Cleanup is going in this direction, I think it's much more productive," says Helm.

Foster agrees that cleaning up the rivers is preferable to trying to extract plastics from the oceans, as it is easier to maintain and monitor a river-based system than one located at sea. Plus, river litter is more concentrated compared to in the oceans. "But again, we need to address why the material ends up in the river in the first place," she says. "The 5p charge in the UK saw a huge reduction

"JUST 1 PER CENT OF MARINE PLASTICS ARE AT THE OCEAN SURFACE, WHILE 94 PER CENT ENDS UP ON THE SEABED"

in the volume of plastic bags on beaches and in the marine environment. This sort of model must be emulated to further reduce plastic pollution."

While it's fantastic that well-meaning people and companies are inspired to find ways to eliminate plastic from the environment, it's clear that we cannot continue living our lives as we always have done, relying on other people to tidy up our mess for us. "We just need to use less," says Thomas Stanton, who researches microplastics at the School of Geography at the University of Nottingham. "We also need better waste management facilities, to ensure that more plastic can be, and is, recycled."

Once we've stopped plastic reaching our oceans, says Foster, the most efficient place to start cleaning up marine litter is on beaches. With everyone in the UK no more than 113km from the sea, that's something we can all get on board with. **SF**

by ALICE LIPSCOMBE-SOUTHWELL (@Mantis_Shrimp)
Alice is managing editor at BBC Science Focus.

WHERE OUR PLASTICS

By 2050 there could be more plastic in the sea than fish. Globally, we produce 380 million tonnes every year, so how much ends up as waste in the ocean?

Illustration by RAJA LOCKEY



Around 380 million tonnes of plastics are produced annually

As of 2015, 8.3 billion tonnes of plastics have been produced by humans since the early 1950s

Of the 8.3 billion tonnes, 6.3 billion tonnes has become waste

By 2050, the total amount of plastic produced by humankind is projected to have risen to 34 billion tonnes

Over 480 billion plastic bottles were sold in 2016 – that's more than 60 bottles for each person on the planet

New bottles are made from only 6.6 per cent recycled plastic

Up to one trillion plastic bags are discarded every year too



Only around 9 per cent of plastic gets recycled



12 per cent gets incinerated

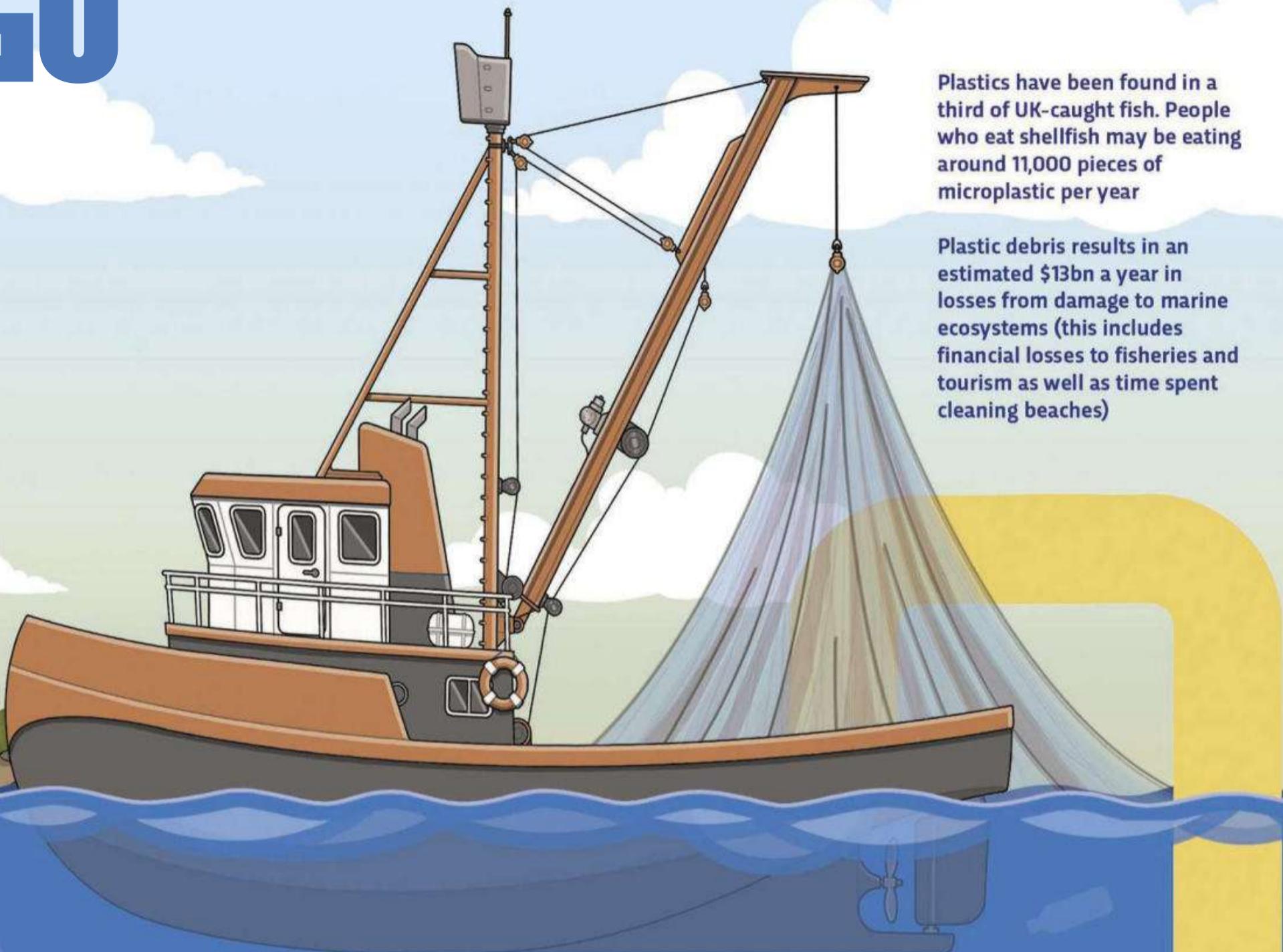
The rest accumulates in landfills or the natural environment.

As much as 13 million tonnes of plastic enters the ocean globally each year – equivalent to the mass of around 85,000 blue whales



The amount of plastic entering the oceans is expected to more than double within 10 years

GO



Plastics have been found in a third of UK-caught fish. People who eat shellfish may be eating around 11,000 pieces of microplastic per year

Plastic debris results in an estimated \$13bn a year in losses from damage to marine ecosystems (this includes financial losses to fisheries and tourism as well as time spent cleaning beaches)

On land, plastic bottles will take 450 years to decompose. At sea, they'll never truly disappear

The bottles break down into microplastics, less than 5mm long

180 species of marine animals have been documented feeding on plastic



There are 51 trillion microplastic particles in the oceans – 500 times more than stars in the Milky Way

70 per cent of ocean waste (including plastic, glass, metal, and other rubbish) sinks to the floor, meaning floating debris is just scratching the surface

DEEP THOUGHT



These remora use modified dorsal fins to attach harmlessly to larger animals, enjoying the protection offered by the host

Think of intelligence in the animal world and you rarely think of fish. But there's growing evidence to show that the various species living in the planet's waters have greater intellects than we've given them credit for

by DR HELEN SCALES

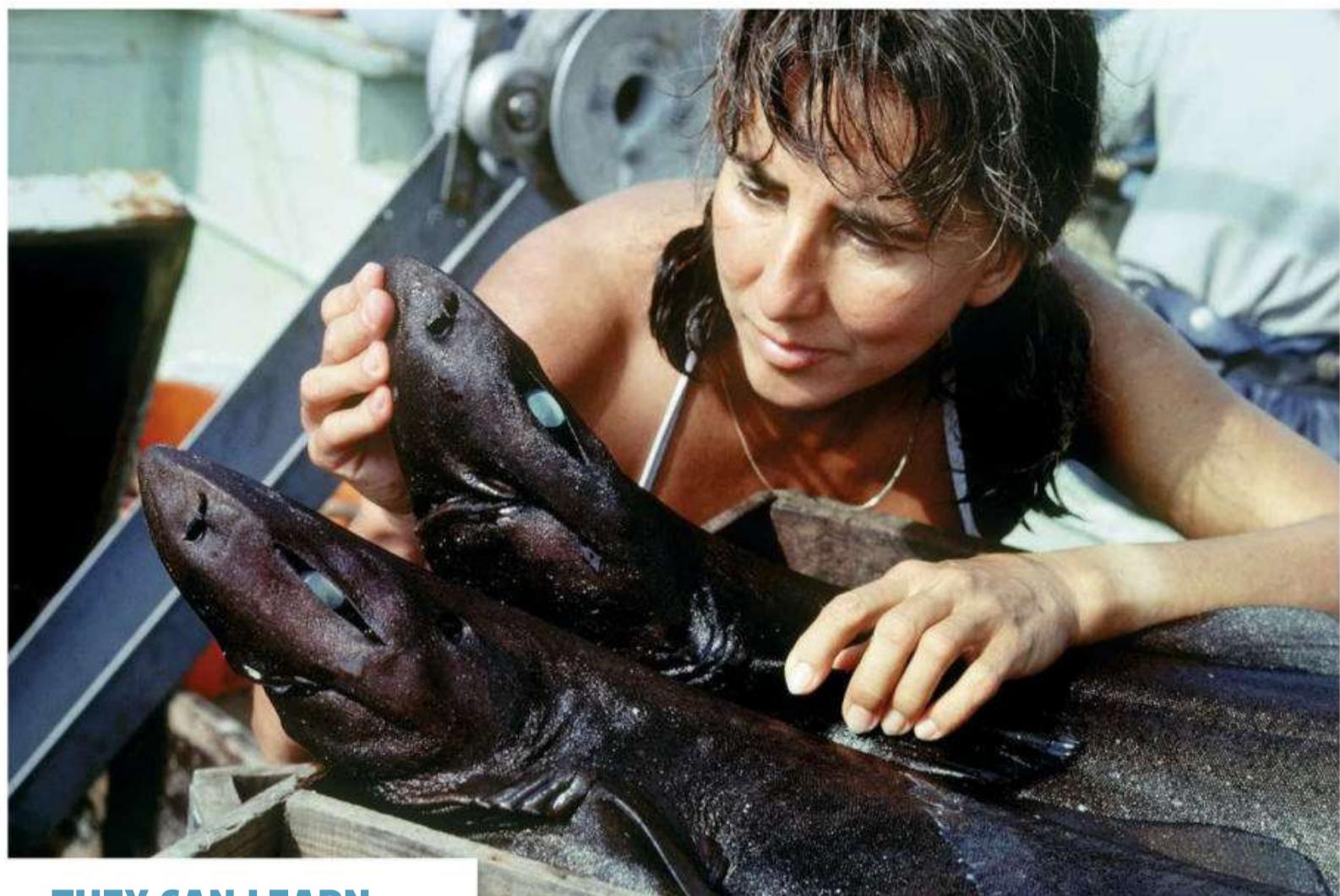
GETTY IMAGES

Many people don't think of fish as being intelligent. Fish brains are too small and they're too distantly related to humans to be clever; they lack feelings; they can't feel pain – at least that's how they've been typecast. Their simple-minded reputation means that people still tend to treat fish differently from other animals, with far less concern for their welfare (just imagine if we slaughtered cows by drowning them in the sea).

In the past, many scientists overlooked fish intelligence and didn't bother testing for it. Those that did often used experiments that weren't relevant for these animals, with senses so different from our own. But the science of fish cognition is catching up, and new studies are showing that fish are much smarter than previously thought. Signs of higher intelligence among fish are not only forcing a rethink of their lives and the way we treat them, but also how brains and animal intelligence evolved. ➤



The pores all over the snout of this lemon shark are called ampullae of Lorenzini. They are present on all sharks and rays, and are a 'sixth sense', allowing the animals to detect electrical signals coming from the movements of their prey – even if they're underneath the sand



THEY CAN LEARN

In the 1950s, US biologist Eugenie Clark first showed that sharks can be trained using food rewards, just like lots of other animals. More recently, researchers in the Bahamas taught captive lemon sharks to press a target with their snout in return for food (image of lemon shark on previous page). When sharks were kept with others that already knew what to do, they learned the task faster than when they were left to figure things out for themselves. This kind of social learning is another important aspect of animal intelligence. Other studies have shown that young lemon sharks prefer to hang out in gangs with other sharks they already know. It's not yet known if they simply distinguish between familiar versus unfamiliar sharks, or if they recognise individuals.

LEFT Marine biologist Eugenie Clark, seen here examining deep-sea sharks, was the first to show that sharks can be trained using food

BELLOW LEFT Studies on manta rays suggest they may be self-aware, yet it's likely that the fishy world contains more examples of this

RIGHT In this coloured 3D scan of a zebrafish, its large eye can clearly be seen in blue

BELLOW RIGHT On the Great Barrier Reef, groupers and eels will buddy up, to increase the efficiency of hunting trips



THEY'RE SELF-AWARE

When scientists from the University of South Florida lowered a giant mirror into an aquarium, two manta rays circled around it, gazing at their reflections. Did the mantas realise they were looking at themselves? Were they self-aware? The scientists involved think so (although not everyone agrees). They argue that when the mantas blew bubbles at their reflections, by dislodging air caught in their gills, this could have been a process known as contingency checking, just like you might wave your hand to check it's your reflection in a distant window.

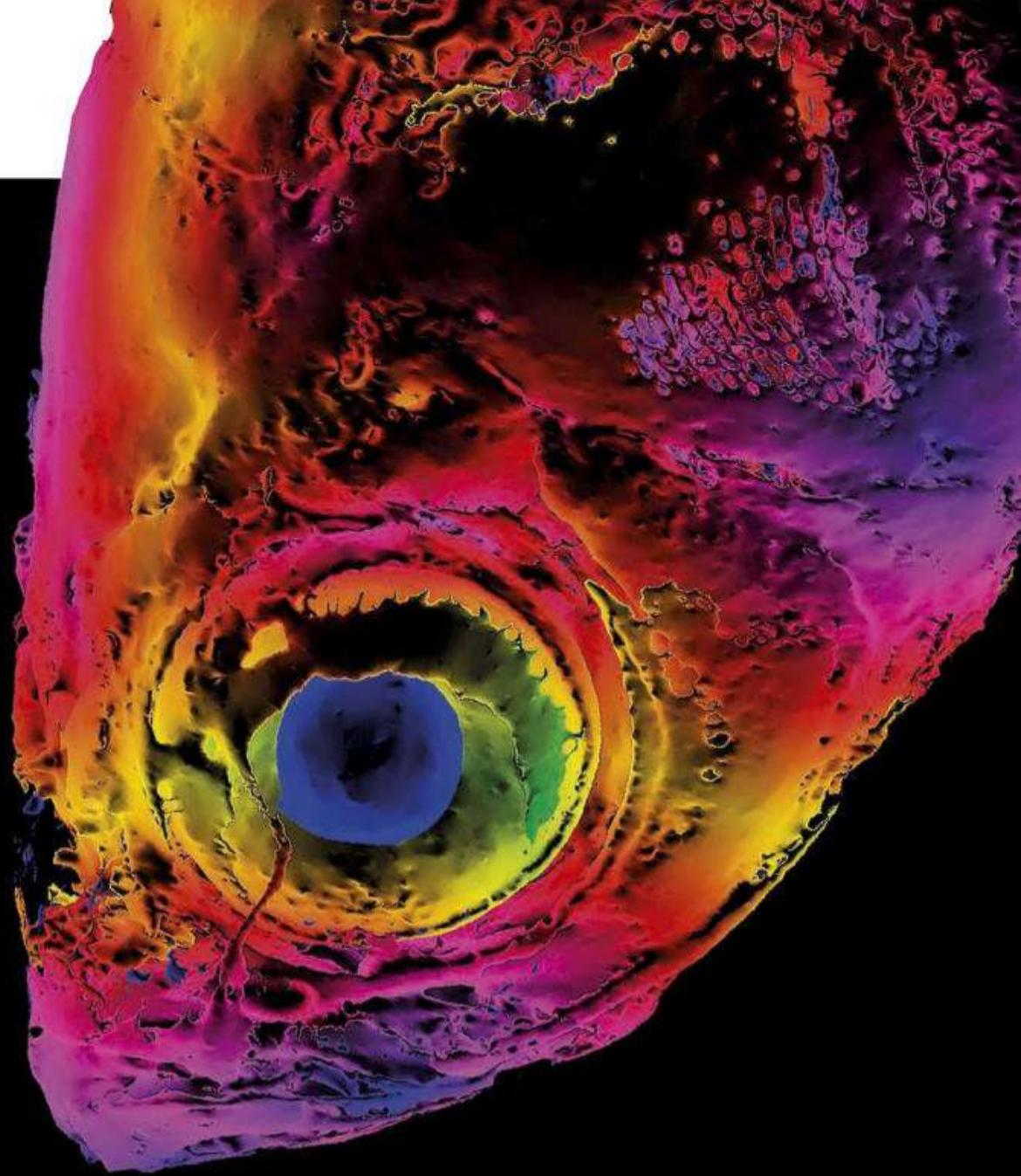
Another self-awareness test involves painting a dot on an animal's body somewhere they can only see in a mirror. A human toddler, adult chimpanzee and even some magpies will reach for and touch the unexpected dot. Of course, manta rays don't have hands or beaks, so there's no easy way of applying this test.

If mantas are eventually added to the small list of self-aware animals, which so far includes mainly mammals and a few birds, it will show that this trait probably evolved many times in the animal kingdom and could perhaps be more widespread than previously thought.

THEY FEEL

It's hard to tell if a fish is suffering. They make no sounds and have no facial expressions. But scientists have begun to work out other ways of gauging their mental state. Zebrafish, the lab rats of the fish world, have been shown to suffer from emotional stress. When trapped in a small net, a zebrafish's body temperature rises by several degrees. Known as emotional fever, this involves the body responding to stress in the same way it does following infection by a pathogen. It was previously thought that only humans suffered from stress like this.

The finding adds to mounting evidence that fish detect and feel pain, even though they lack a neocortex, which is the mammalian brain region responsible for pain perception. Following findings like these, standards for the ethical treatment of fish are gradually catching up to those for other animals. In Britain it's illegal to mistreat pet fish (in recent years there have been several convictions of cruelty to animals as a result of goldfish being swallowed live) and in Germany recreational fishermen must keep, humanely kill and eat any fish they catch, without releasing them again, otherwise their sport is deemed to cause unnecessary suffering.

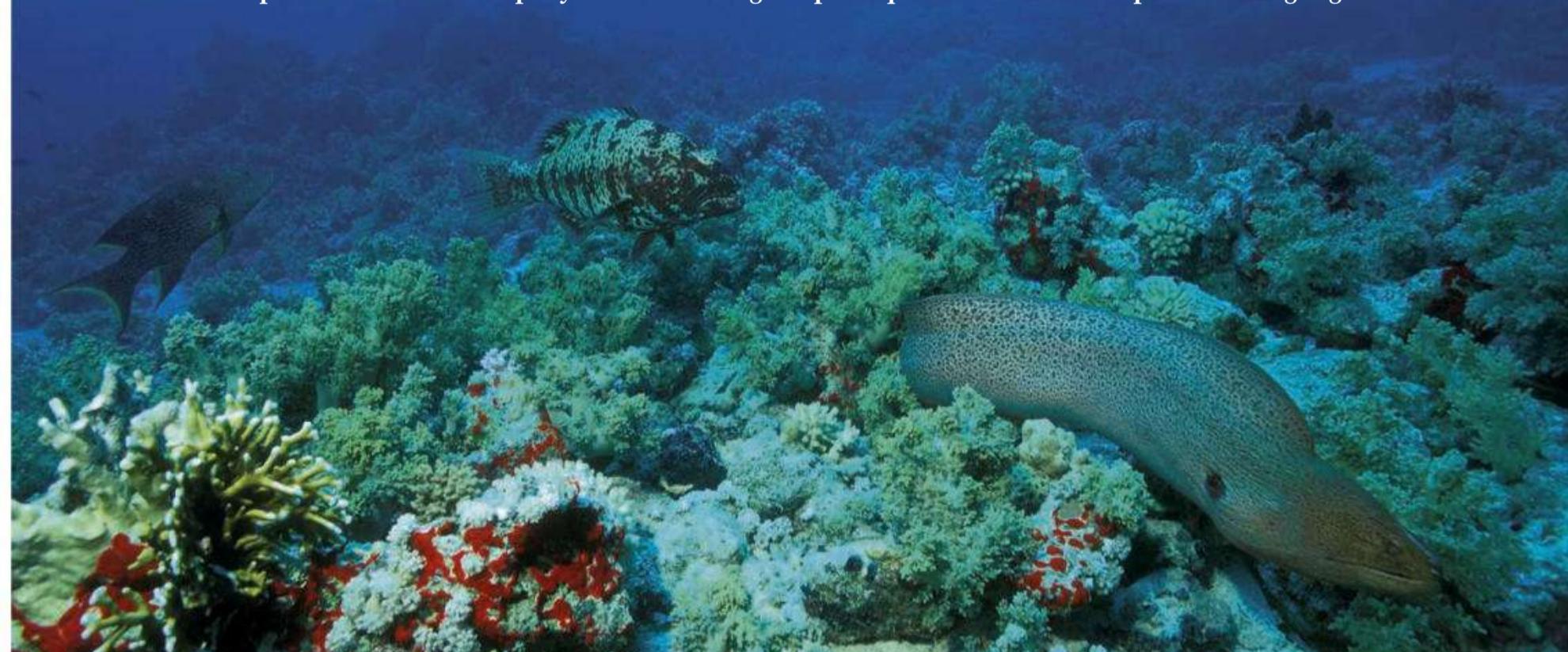


THEY POINT

Several years ago, scientists diving on the Great Barrier Reef spotted groupers behaving very strangely – they were doing headstands and shimmying their bodies. A team of diving scientists patiently watched many groupers doing this before finally working out what was going on.

When a grouper chases a smaller fish into the reef, usually it's too big to follow. So the grouper waits for another hunter to pass by, often a moray eel, then does a headstand to point to where the prey fish is hiding.

Many times, scientists saw eels responding to a grouper's gestures by sliding into the reef and either catching the prey or scaring it out of the reef and into the grouper's waiting jaws. A grouper and an eel will often set off on a hunting spree together across the reef. This is the first known case of fish forming interspecies hunting partnerships and pointing to each other. Using gestures like this is uncommon in the animal kingdom, and it's thought to be an important prerequisite for the development of language in humans. ☠



5 GOLDFISH MYTHS BUSTED

That denizen of bowls throughout the country is deserving of so much more...



1 IT'S FINE TO KEEP GOLDFISH IN SMALL BOWLS

Nope. While goldfish *can* survive in cramped conditions, it's not good for them. To live to their full lifespan and size (they can reach 45cm), they need properly aerated, treated and filtered water.



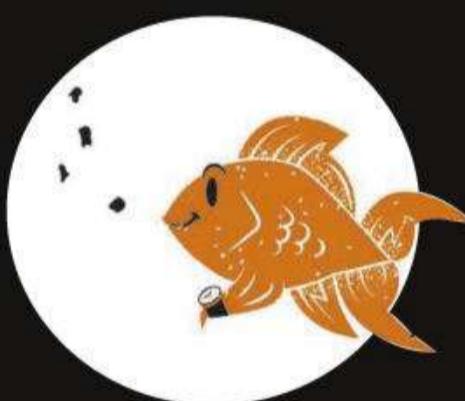
2 EACH VARIETY OF GOLDFISH IS A DIFFERENT SPECIES

Wrong again. All goldfish are the same species, *Carassius auratus*, a type of carp originally from East Asia that's been selectively bred for hundreds of years.



3 YOU CAN'T TRAIN A GOLDFISH TO DO TRICKS

Yes you can! Like training a dog with food rewards, you can teach goldfish to swim through hoops, slalom between posts and even push a mini football into a net.



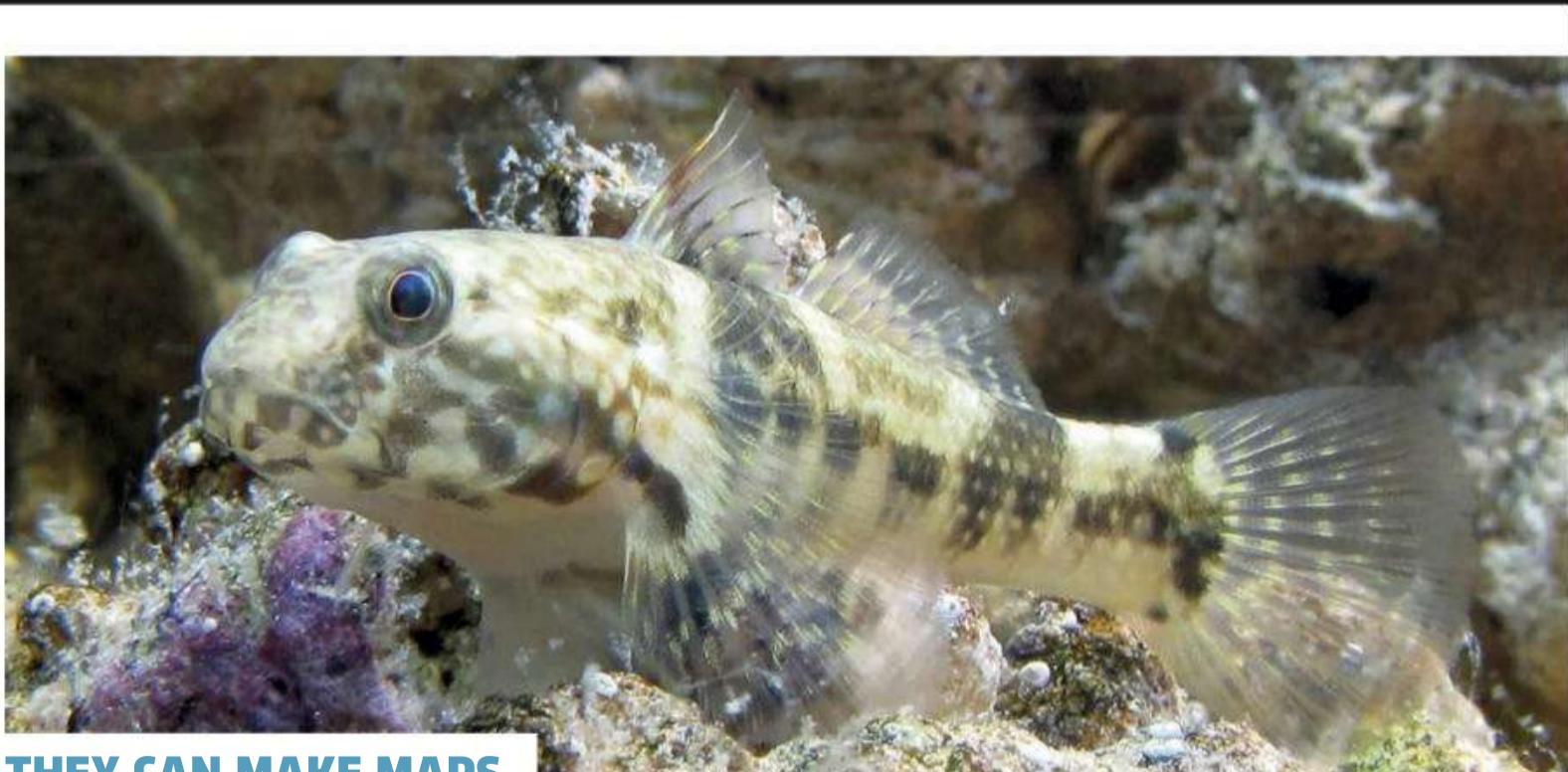
4 GOLDFISH HAVE A THREE-SECOND MEMORY

Wrong! Goldfish remember things for months. Feed your pet goldfish at one end of their tank each morning and the opposite each evening, and they'll quickly learn where to wait.



5 GOLDFISH ONLY LIVE FOR A COUPLE OF YEARS

Not true. In fact, the average lifespan of a captive goldfish is 5 to 10 years, and if they're carefully looked after they can live well into their 30s or 40s.



THEY CAN MAKE MAPS

Along the shores of the Gulf of Mexico live small fish called frillfin gobies. Swimming around at high tide they memorise features of the seabed and figure out where rockpools will form when the water recedes. At low tide, if a goby gets stuck with a predator in a pool, it knows which emergency escape route to take. It leaps in precisely the right direction to land in a neighbouring pool. When scientists remove these fish and then return them to their territories weeks later, the gobies still remember their mental maps and jump to safety.

LEFT Frillfin gobies can create mental maps of their territories, both above and below the waterline, and remember them for weeks at a time

ABOVE RIGHT Cleaner wrasse, like the one seen here in the mouth of another fish, are capable of remembering individual fish and know what services to offer

RIGHT Archerfish understand physics, adjusting their water jets to compensate for the way that light bends as it passes from water to air



THEY CHEAT

If you want proof that fish have more than the fabled three-second memory, look no further than cleaner wrasse. Every day, they pick parasites and dead skin from hundreds of other fish – and they remember each individual fish and adjust their services accordingly.

Scuba-diving scientists have spent hundreds of hours watching cleaner wrasse at work on coral reefs. They've seen that when large predators, such as groupers, show up, the wrasse offer an honest service. But when they're cleaning harmless herbivores, like parrotfish, the wrasse will sometimes cheat. Instead of removing parasites, they slurp slime from the fish's skin. Not only is slime more nutritious than parasites, but it also contains sunscreen, which stops the wrasse getting sunburnt. Even when it cheats, a wrasse apologises by massaging the other fish with its fins and persuading them not to swim off in a huff.

SD BEAZLEY/WIKIPEDIA COMMONS, FFLPA, GETTY IMAGES. ILLUSTRATIONS: JAMES OLSTEIN

THEY RECOGNISE FACES

It might strike you as an odd thing to do, but scientists at the University of Queensland and the University of Oxford have taught archerfish to recognise human faces. They positioned a computer screen above an aquarium tank and trained the fish to spit water at a particular face, giving them food whenever they hit the right target. When they were shown dozens of other faces, the archerfish kept on shooting at the ones they'd learned to associate with food.

Distinguishing between faces is a complex task involving spotting subtle differences in the same set of features (two eyes, a nose and a mouth). Obviously, archerfish didn't evolve a specific ability to recognise human faces, but the study shows that even without a big brain, fish can recognise slight differences in their surroundings, presumably including other things that are important to them, such as predators and prey.



THEY MAKE TOOLS

Tool use is a sign of higher intelligence that various fish have. Archerfish use droplets of water as bullets to shoot insects off vegetation above the water's surface; they can even adjust the aim to compensate for the way light bends as it passes between air and water, and still hit their target.

A few years ago, researchers in Norway saw captive Atlantic cod inventing a new tool to feed themselves. Three cod, in two separate tanks, accidentally got their identification tags tangled in a string that released food from an automatic feeder. Beforehand, the cod had learned to pull the string with their mouths to get food. But these three cod worked out that it was much faster to deliberately hook their tags on the string, then spin around and gobble the food. **SF**

by DR HELEN SCALES
*Helen is a marine biologist, broadcaster and author. Her next book, *The Sea Beneath Us* (£16.99, Bloomsbury Sigma), will be out in February 2021.*

LIFE AT SEA

AS SEA LEVELS ENCROACH ON THE LAND, COULD WE MOVE PEOPLE TO THE OCEANS?

In 2007, Marc Collins Chen was working as the minister for tourism in French Polynesia when reports started to emerge that the Pacific islands would be under threat from rising sea levels in the coming decades. "There wasn't consensus around when this would happen," he says. "But there was a sense of doom."

Today, Chen is CEO of Oceanix, a company based in Hong Kong that's developing concepts for floating cities. He's now been working on the problem for 13 years. "If you're a Pacific Islander and many of your islands are at sea level, you have to look at a solution," he says.

In 2019, Oceanix announced a collaboration with the Bjarke Ingels Group (BIG) and MIT's Centre for Ocean Engineering, creating a concept for a city of 10,000 people. It was unveiled as part of the UN's New Urban Agenda, a plan to create ways for the world's growing population to live more sustainably.

The 10,000 figure is an estimate, says Chen, and the way the city works means it will be able to host as few or as many people as necessary. The city will be made up of floating, roughly triangular platforms, each around two hectares in area and home to 300 people. Each platform, or 'neighbourhood', will generate its own renewable electricity from the waves and Sun, and the population can be increased by adding more of these modular platforms.

Alongside renewable energy, the city will grow its own plant-based food, and treat and reuse all waste water. "If you wanted to feed everybody with beef and chicken, you'd need so much surface area and freshwater," says Chen. "It'd become economically unfeasible."

The platforms will be secured to the seabed with biorock, which is a material already being used to create artificial reefs around the world. A low-voltage electrical current is passed through a steel frame,



which electrolyses the seawater around it and causes charged particles (ions) to build up on its surface, coating the steel in a rocky substance that's as strong as concrete.

Making sure the cities have a positive impact on the environment is crucial, Chen says. The UN uses 'ecological footprints' to measure the impact people have on the natural world, measured in global hectares per person. At current population levels, our planet has only 1.7 global hectares (gha) of biologically productive surface area per person. At the moment, the UK has a footprint of 7.9 gha per person, which means we're using more than we have. As the world's population increases, we need to be reducing our individual footprints. Chen says that Oceanix could have a footprint of as little as 0.5 gha per person, helping to reduce the strain on our ailing planet.

This might all sound quite far-fetched, but Chen believes it will happen, and soon. The company is aiming to have a prototype of the floating city in place within the next few years, although the location has not yet been pinned down.

by ABIGAIL BEALL (@abbybeall)
Abigail is a science journalist, based in Leeds.

BJARKE INGELS GROUP

Residents will walk, cycle or boat through the city, with solar-powered ferries transporting them to the mainland





ALL YOUR QUESTIONS ANSWERED



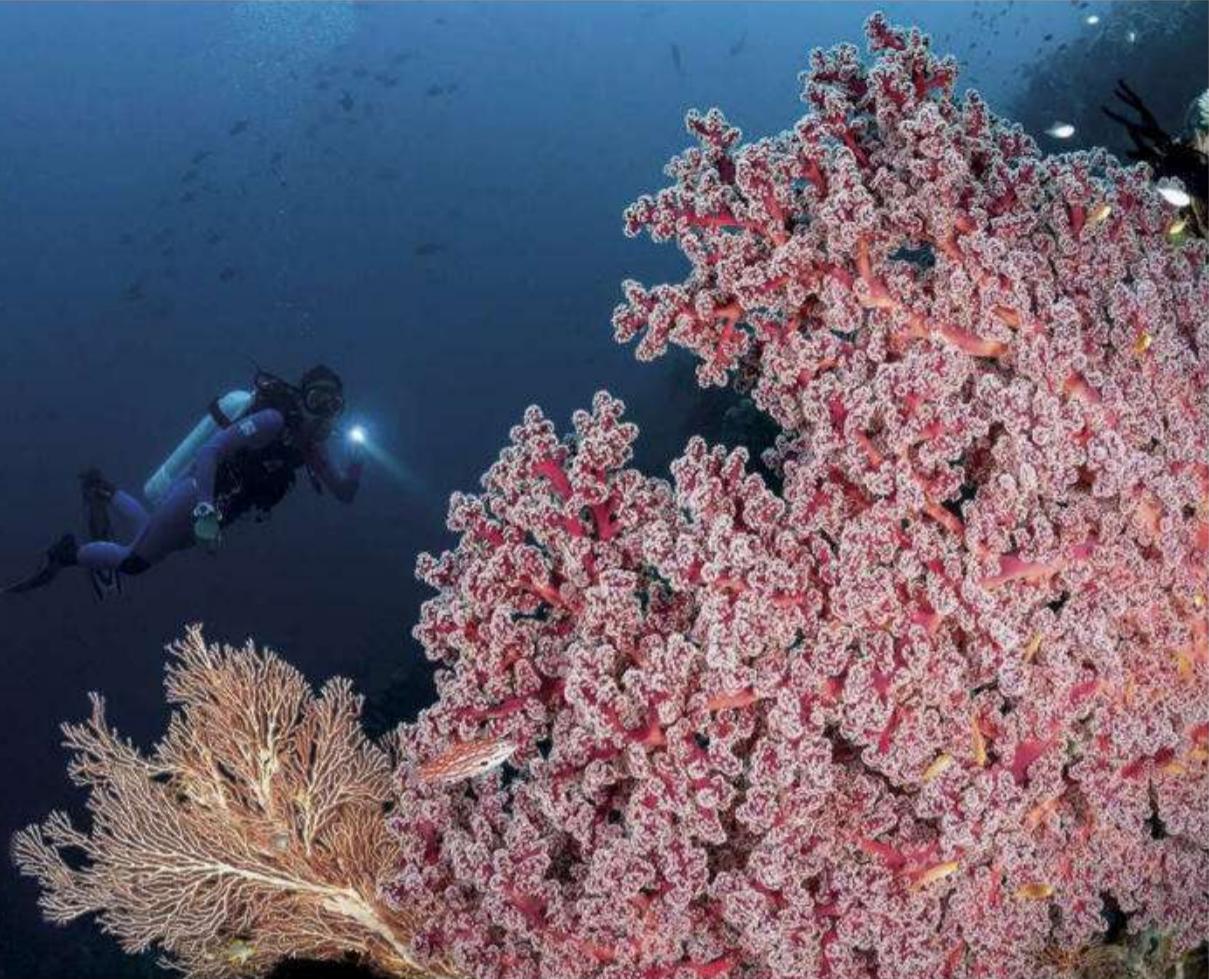
WHAT'S THE DIFFERENCE BETWEEN A SCHOOL, A SHOAL AND A POD?

When fish, shrimp or other aquatic creatures swim together in a loose cluster, this is typically called a shoal. It can be a mix of different species. A school is a group of the same fish species swimming together in synchrony; turning, twisting and

forming sweeping, glinting shapes in the water. Fish probably do this to confuse predators and to save energy (by using the 'slipstreams' of other fish). Pods are herds of marine mammals including whales, dolphins, walruses and seals.

HOW DEEP CAN CORAL LIVE?

In the tropics, it was long thought that corals build reefs only in shallow waters, down to around 40m. These microscopic creatures have algae living inside them that need sunlight to photosynthesise. Lately, using new and improved diving equipment, scientists are discovering much deeper corals living in the 'twilight zone' down to 160m, even though very little sunlight trickles that far down. It's possible these deep corals could help recolonise shallower reefs damaged by impacts like coral bleaching. Other types of coral – without algae partners – live around the world, thousands of metres beneath the waves.



HOW DO MUSSELS STICK TO WET ROCKS?

Hundreds of sticky threads (byssus) glue mussels to slippery, wave-pounded rocks. Mussels make the threads by squeezing quick-setting liquid protein into a groove in their muscly foot. The key ingredients are called 'mussel adhesive proteins', or MAPS, which form weak bonds with the rock. They are being investigated as inspiration for surgical glues, and for the production of hard-wearing, self-healing polymers in replacement joints. Synthetic MAPs may even be used to fix anti-fouling chemicals to the bottoms of boats, to stop molluscs from sticking.

GETTY IMAGES X4



WHAT WOULD HAPPEN IF THE SEA ROSE BY 2M?

In the last couple of decades, the sea level has risen by about 3.2mm per year – double the average rate last century. A further 2m rise by 2100 is predicted by many experts. This would put a lot of Cambridgeshire permanently underwater, as well as much of Hull, Great Yarmouth and Glastonbury. But sea level isn't constant around the globe. Ocean currents and the shape of the land masses mean the waters of the South Pacific and China Sea are already 30cm higher than the average. Falling salinity due to increased rainfall lowers the density of seawater, so the sea level in these areas rises faster too.

In 2016, more than 3.7 million people were affected by floods in Bangladesh

Forty per cent of the world's population lives within 100km of the coast, while 250 million people live less than 5m above sea level. Hurricanes and storm surges can magnify even small sea level rises. Flood levels that would previously be expected just once a century will occur on average once a decade. The US has 20,000km (12,400 miles) of coastline and protecting it will cost \$15bn. Bangladesh fares much worse. It will need 8,000km of dykes over 10m tall to protect it, and without them will lose more than 16 per cent of its total land area, including the Sundarbans mangrove forest – one of the last homes of the Bengal tiger.



WHY DO BEACHED WHALES OFTEN DIE?

Death is often due to dehydration. Whales have an incredibly thick layer of insulating blubber. Without the water to keep them cool, they overheat and lose too much water via evaporation from their lungs. Whales can also drown as the tide comes in because they are lying on their side and the water covers their blowhole before it's deep enough for them to swim free. Even if they do get back into the water, many whales die a few hours later because their huge weight causes crush injuries that release toxic breakdown products into their blood when the pressure is removed.



IS ANTARCTICA MELTING?

Antarctic sea ice undergoes an annual cycle of freezing and melting, reaching its maximum extent in October and then melting. In the past few decades, the maximum amount of Antarctic sea ice has increased slightly, but on land, it's a different story. While a few areas of the frozen continent's gigantic ice sheet have been growing, overall Antarctica is losing ice, with glaciers in West Antarctica undergoing the most rapid melting. Ice shelves fringing the Antarctic landmass, where land ice meets the ocean, are also shrinking. As global temperatures increase, scientists expect to see further melting, adding to global sea level rise.

CAN CORAL REEFS RECOVER FROM BLEACHING?

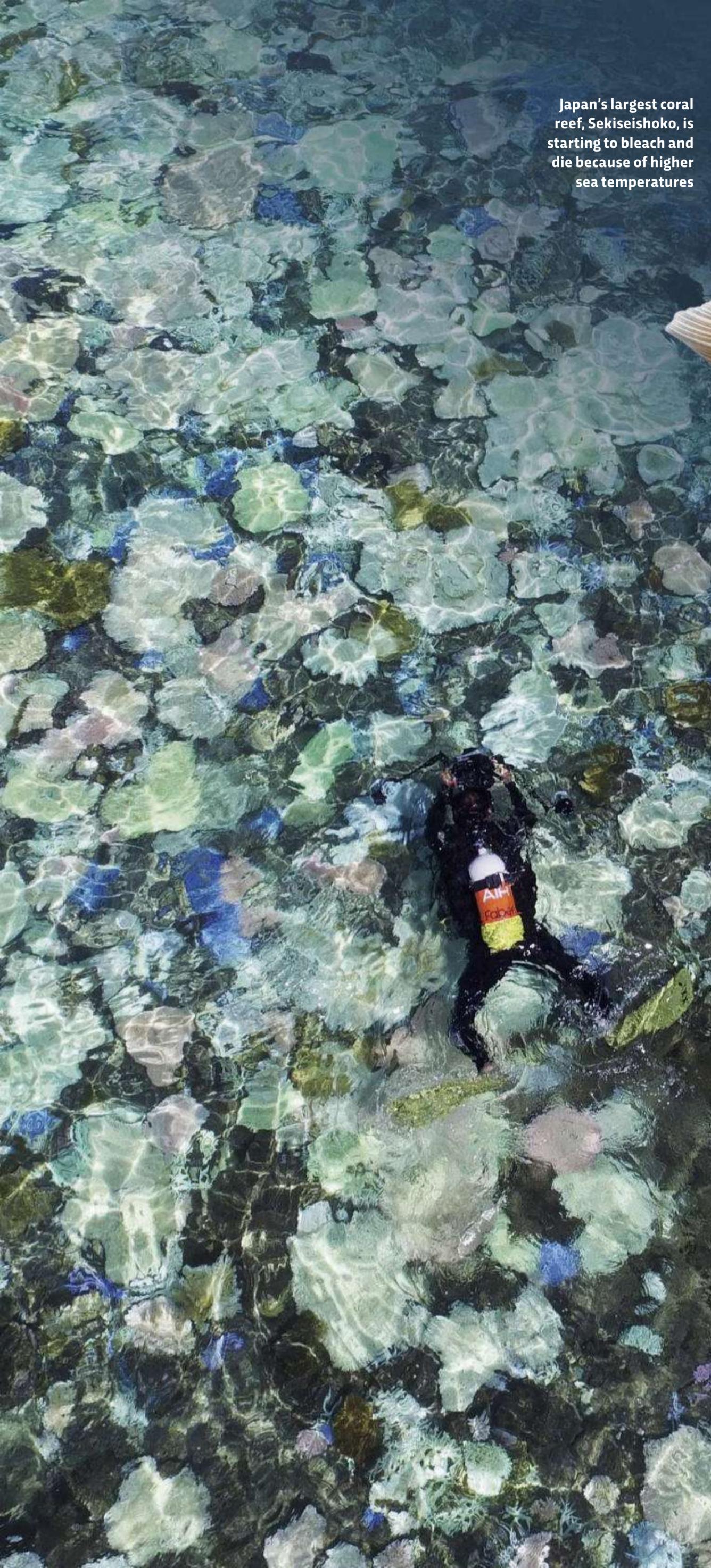
Coral bleaching occurs when warmer sea temperatures cause coral to expel the tiny algae that live in their tissues. Without these algae, corals are more susceptible to disease, with impaired growth and reproduction rates. If increased temperatures are short-lived, surviving corals can sometimes regrow their algae within a few months. When bleaching is localised, healthy coral nearby can also help repopulate the area. But in instances of more severe, extensive or repeated bleaching events, or when additional stresses such as pollution or ocean acidification come into play, large swathes of coral may die and recovery can take decades.

CAN FISH SEE IN THE DARK?

It's not strictly seeing as we know it, but fish have rows of pressure-sensitive organs running down each side of their body called the lateral line, which allows them to sense nearby animals from the pressure changes in the water. Sharks and electric eels also have special sense organs that allow them to detect the tiny electric fields generated by other animals.



Japan's largest coral reef, Sekiseishoko, is starting to bleach and die because of higher sea temperatures



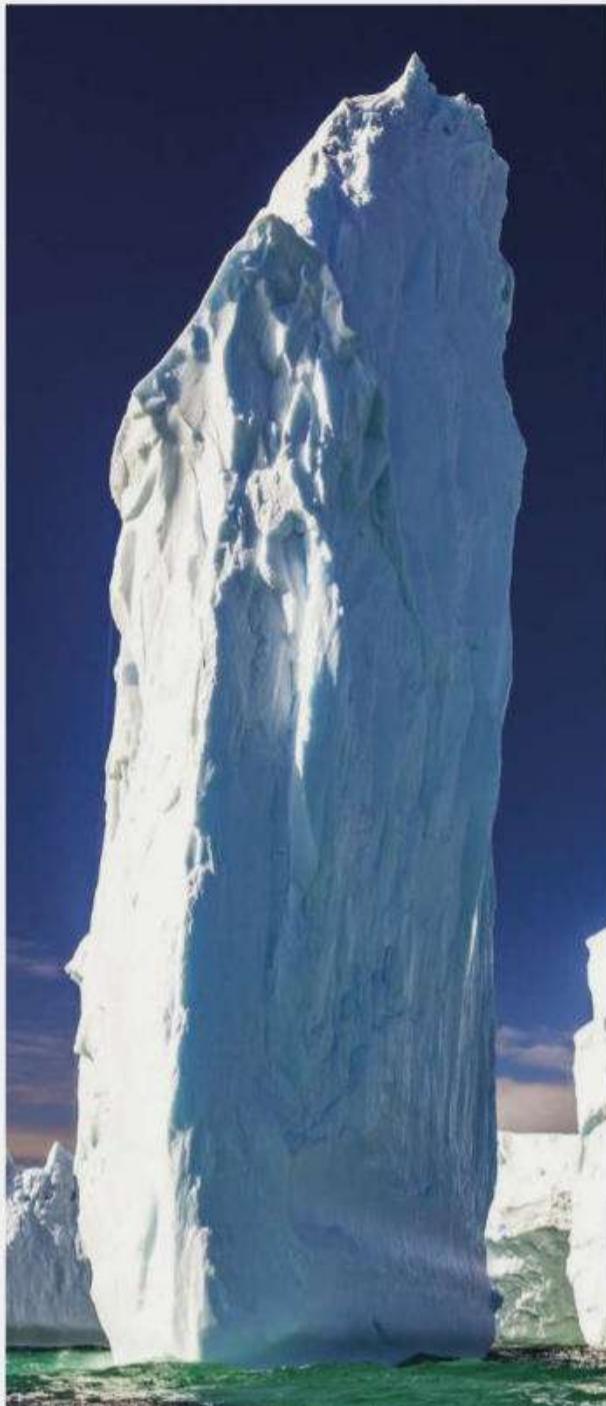
DO FISH DRINK?

Depending on where they live, fish either drink a lot or pee a lot. In the sea, a fish's body is less salty than its surroundings, so it loses water across its skin and through its gills via osmosis. To stop themselves dehydrating, marine fish drink masses of seawater and produce a trickle of concentrated urine. When migrating fish like trout and salmon move into rivers and lakes, they face the opposite problem and risk absorbing too much water until eventually, their cells begin to swell and burst. To avoid this, they switch from being heavy drinkers to plentiful urinators.



HOW DO SHARKS SMELL BLOOD UNDERWATER?

When you smell something in the air, it's because scent molecules have dissolved into the wet lining of your nose. Smelling underwater is no different, except that the molecules are already dissolved in the seawater. It's a myth that sharks can smell a single drop of blood from a mile away. Sharks actually have roughly the same sensitivity as other fish and can detect smells at between one part per 25 million and one part per 10 billion, depending on the chemical, and the species of shark. At the top end, that's about one drop of blood in a small swimming pool.



WHY ARE SOME ICEBERGS GREEN?

Most icebergs have a bluish tinge because the ice absorbs longer wavelengths of visible light (reds) better than shorter ones (blues), reflecting more blue light back towards our eyes. However, some Antarctic icebergs are a striking emerald green, and have long puzzled scientists. The latest theory is that these 'jade bergs' are caused by iron oxide minerals in the ocean. As glaciers move over the Antarctic mainland, they scrape its surface, producing powdered rock rich in iron oxides that eventually makes its way into the sea. Scientists believe that pockets of the resulting iron-rich water then freeze onto the underside of icebergs, with the combination of orange-tinted iron oxide and blue ice producing a deep green hue.

ARE THE OCEANS GETTING SALTIER?

Seawater tastes salty because of the action of rain on exposed rocks. The compounds most likely to find their way into the sea are, naturally enough, the most water-soluble ones, and these are rich in chlorine and sodium ions – the raw ingredients for common salt. As this process has been operating for billions of years, there's no doubt oceans have become saltier over time. In fact, the real mystery is why they aren't now saturated with the stuff, making them as

lifeless as the Dead Sea. Somehow, the concentration has remained at just a few per cent for at least half a billion years. Exactly how isn't clear, but one theory, suggested by British ecologist James Lovelock, involves the vast, mat-like colonies of bacteria found in coastal lagoons around the world. The Sun's heat triggers evaporation of the water, leaving behind its salt content trapped on the coast and unable to dissolve back into the sea.



WHICH CREATURE MAKES THE BIGGEST SEASHELL?

Seashells are the exoskeletons of animals called molluscs, including snails, nautiluses, mussels, scallops and oysters. The biggest are giant clams, *Tridacna gigas*. Their twinned shells can grow to well over a metre across and tip the scales at 200kg, the same as two newborn elephants. Giant clams, like all shell-making molluscs, sculpt their protective homes from calcium carbonate and gradually expand them throughout their lives. They inhabit coral reefs and can live for at least a century. Demand for their meat as a delicacy in many countries is making them vulnerable to extinction.



WHY DOES THE SEA SMELL LIKE THE SEA?

Saltwater by itself doesn't have any smell, but the things that live in it certainly do. The rather stale, sulphury smell is dimethyl sulphide, produced by bacteria as they digest dead phytoplankton. At low tide, you'll also smell chemicals called dictyopterenes, which are sex pheromones produced by seaweed eggs to attract the sperm. And on top of all this is the 'iodine' smell of the sea, which is actually the bromophenols produced by marine worms and algae.

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Science Focus

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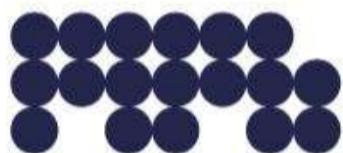
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